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TECHNICAL REPORT

WHITE OAK LABORATORY

EXPERIMENTAL INVESTIGATIONS OF THE EFFECTS OF UNDERWATER EXPLOSIONS ON SWIMBLADDER FISH, I: 1973 CHESAPEAKE BAY TESTS

BY
Joel B. Gaspin

20 JUNE 1975

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The experiment described in this report was designed to examine the role of various shock wave parameters in damage to swimbladder fish. Caged spot and white perch were placed at various positions in the vicinity of underwater explosions. Eleven shots were fired. Pentolite spheres of 1 to 68 pounds were used at burst depths of 5 to 70 feet. The fish specimens were placed at depths of 5 to 40 feet. The pressure-time signal at each location was recorded, and the damage to each fish specimen was determined by dissection.
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The experimental details are given and the fish damage and pressure-time data are summarized.

The results of the preliminary data analysis are as follows: none of the simple shock wave parameters of peak pressure, impulse or energy, alone was found to be adequate for the prediction of fish damage. For spot, a correlation of damage with the drop in pressure at the time of arrival of the surface reflected shock wave was found. For white perch, all significant damage, at peak pressures below 200 psi, occurred near a shock wave duration of 0.65 msec. At the present time, no general damage rule for swimbladder fish has been extracted from these data.

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EXPERIMENTAL INVESTIGATIONS OF THE EFFECTS OF UNDERWATER EXPLOSIONS ON SWIMBLADDER FISH, I: 1973 CHESAPEAKE BAY TESTS

The Navy is required to consider the possible adverse environmental effects of its research operations. When such operations involve the detonation of underwater explosions, one of the environmental factors to be evaluated is the effect of these explosions on nearby marine life. Up to the present time, the state of knowledge has not been adequate to realistically predict such effects.

The experiment which is the subject of this report, is part of a continuing study of the effects of underwater explosions on swimbladder fish. This class of fish is particularly vulnerable to explosions, and includes the majority of fish with sports and commercial value. This study will result in an improved capability to predict such effects, and will be useful in connection with a variety of Naval research operations.

This study is part of the pollution abatement program of the Naval Sea Systems Command and was supported by Task SEA 33200520024, "Environmental Effects of Explosive Testing".

Julius W. Enig
JULIUS W. ENIG
By direction

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EXPERIMENTAL INVESTIGATIONS OF THE EFFECTS OF UNDERWATER EXPLOSIONS ON SWIMBLADDER FISH

I: 1973 CHESAPEAKE BAY TESTS

1. INTRODUCTION

1.1 The damage done to marine life by underwater explosions has been a continuing problem. Those who use underwater explosions for seismic exploration and demolition, as well as explosions and weapons researchers, have been unable to provide realistic predictions of the fish kill to be expected in their operations. In order to make an estimate of the expected biological impact of an underwater explosion, two questions must be answered: First, what is the distribution of biologicals in the region surrounding the explosion, and of what species are they? Second, what is the probability that a member of a given species, experiencing specific explosion induced pressures, will be mortally injured? This report describes an experiment performed to gather data on the second of these questions.

1.2 The experiment emphasized damage to swimbladder fish. In addition, a small amount of data on crabs and oysters was gathered, and is described in Appendix A.

2. Background

2.1 We are particularly concerned with the lethal zone around an underwater explosion for fish with swimbladders. This class of fish includes most fish of commercial or sports value. In addition, swimbladder fish are more vulnerable to explosions than fish lacking this organ, such as flat fish and shell fish.

2.2 There have been a number of experimental studies of the effects of underwater explosions on swimbladder fish. A summary of the implications of this work is given by Christian (1973)*. A comprehensive bibliography has been compiled by Simonstad (1974). A good deal of the work reported involves special situations and non-standard charge configurations, which make extensions of the lethal zone determinations impossible. Two generalized damage rules have been put forth.

*For the convenience of the reader, all references are also listed in the bibliography on page 40.

Christian, E. A., 1973, "The Effects of Underwater Explosions on Swimbladder Fish," NOL Technical Report NOLTR 73-103.

Simenstad, Charles A., 1974. "Biological Effects of Underground Nuclear Testing on Marine Organisms. I. Review of Documented Shock Effects, Discussion of Mechanisms of Damage, and Predictions of Amchitka Test Effects". In "Processings of The First Conference on The Environmental Effects of Explosives and Explosions," compiled by George A. Young, Naval Ordnance Laboratory Report NOLTR 73-223, 12 Feb 1974.

Lavergne (1970) proposes a lethal range varying as the square root of the charge weight. Hubbs and Rechnitzer (1952) and NOL (1947), among others, propose a lethal range which depends on the peak pressure from the explosion. This is essentially a variation with the cube root of charge weight. In addition to the fact that these damage rules differ significantly from one another, neither is able to explain the collection of available data adequately.

2.3 A new approach to correlating fish damage with the explosion pressure field was suggested by Christian (1973). Christian's theory postulates two damage zones for swimbladder fish caused by underwater explosions. The first, an "immediate kill" zone, is a spherical region surrounding the explosion; here, the peak overpressure is probably the main component in fish kill. The second "remote damage" zone was equated with the region of bulk cavitation. In the region of bulk cavitation which is generated by an underwater explosion, the water itself is ruptured by negative pressures.

2.4 When a strong shock wave from an underwater explosion is incident on the air-water interface, the reflected pulse tends to create sizable tensions in the water. Since water can only withstand weak tension*, it will tend to rupture or cavitate, producing an extensive region in the water filled with bubbles of water vapor. This process of bulk cavitation was treated by Gaspin and Price (1972), who give computer routines for the calculation of the extent of the cavitated region. Since, as a first approximation, fish tissue and water have similar physical properties, it may be postulated that a swimbladder fish would be seriously injured at locations where the water cavitates.

2.5 It is the "remote damage" zone in which the large majority of fish kill was to be expected. This theory was used as a planning tool in designing our experiment.

3. Plan of the Experiment

3.1 The experiment was conceived to gather high quality pressure-time (p-t) records of the explosion signals, and a quantitative evaluation of fish damage, for potential correlation. As a planning tool, the idea of bulk cavitation as an important factor in swimbladder fish mortality was adopted. An essential part of the program was obtaining p-t records at selected positions where specimen fish were located. The p-t records could be used to determine if bulk cavitation occurred at a given location; as well as yielding a complete pressure history, for correlation with fish damage, if the cavitation idea failed.

Laverge, M., 1970, "Emission by Underwater Explosions," Geophysics, Vol. 35, No. 3, pp. 419-435.
Hubbs, C. L. and A. B. Rechnitzer, 1952, "Report on Experiments Designed to Determine Effects of Underwater Explosions on Fish Life," California Fish and Game, Vol. 38, No. 2, pp. 333-336.
NOL (Naval Ordnance Laboratory), 1947, "Report of Conference on The Effect of Explosions on Marine Life," unpublished manuscript
*It is generally assumed that water can withstand no tension, and cavitates if the pressure tends to drop below absolute zero.
Gaspin, J. B., and R. S. Price, 1972, "The Underpressure Field from Explosions in Water as Modified by Cavitation," NOL Technical Report NOLTR 72-103.

3.2 The test plan was configured so as to place some cages within, and others outside of the expected zone of cavitation. The maximum overpressure and impulse were varied so as to attempt to separate out the effects of these variables, insofar as conditions permitted. Fish targets at each location were both swimbladder and non-swimbladder species.

3.3 Modification of the Pressure Waveform by Cavitation

3.3.1 The theoretical calculations found in the literature for the extent of the bulk cavitation region have never been adequately verified experimentally. The direct observation of cavitation, by high speed underwater photography, was not within the scope of the present experiment. Instead, a method of determining the occurrance of cavitation from a p-t record was used.

3.3.2 The manner in which the explosion pressure waveform is modified by the occurrance of cavitation is discussed in detail by Gaspin and Price (1972). Briefly, there are two distinctive characteristics. At the time of arrival of the surface reflected shock wave, the total pressure in the water reaches absolute zero. In addition, the waveform of the negative going surface reflection is changed. The situation is summed up in Figure 1. The five pressure-time curves are lettered to correspond to the five successively deeper points indicated in the sketch. At point "a", the surface reflection does not lower the pressure as far as absolute zero, and no cavitation occurs. At this point, the surface reflected pressures may be reasonably calculated assuming an image source of equal strength to the actual source, and a negative exponential wave form. At point "b", on the upper edge of the cavitated zone, the reflected pressure is just sufficient to lower the total pressure to absolute zero and cavitation occurs. After the pressure reaches zero, it stays relatively stable at that level and eventually merges into succeeding events (closure). At points "c" and "d", within and on the lower boundary of the region, the reflected wave form shows a sharp negative spike below absolute zero. This net tension results from the finite time necessary for the water to cavitate. On many recordings, this spike is not apparent due to inadequate frequency response. Following this spike, the pressure returns to a more or less stable "plateau" pressure of absolute zero. As the wave propagates to point "e", the wave form retains the general features which characterized "c" and "d", but the reflected pressure is no longer adequate to produce cavitation.

3.3.3 Measurement of the plateau pressure is inherently imprecise on most p-t records. This is due to the fact that the excursion below ambient pressure is only a small fraction of the peak overpressure. Because of the need for improved information on the negative pressures associated with the shock pulse, a new method of recording was devised for these tests. Clipping off most of the positive excursion allows the gain of the recording system to be increased to the point where the negative pressure (relative to ambient) is a sizable part of the full dynamic range of the recording system. This recording modification is discussed in Section 4.

3.4 Biological Specimens

3.4.1 All handling of biological specimens was done under contract by personnel of the Chesapeake Biological Laboratory (CBL) of the University of Maryland. Two species of swimbladder fish, spot (*Leiostomus xanthurus*) and white perch (*Morone americana*) were selected as swimbladder specimens, and hogchokers

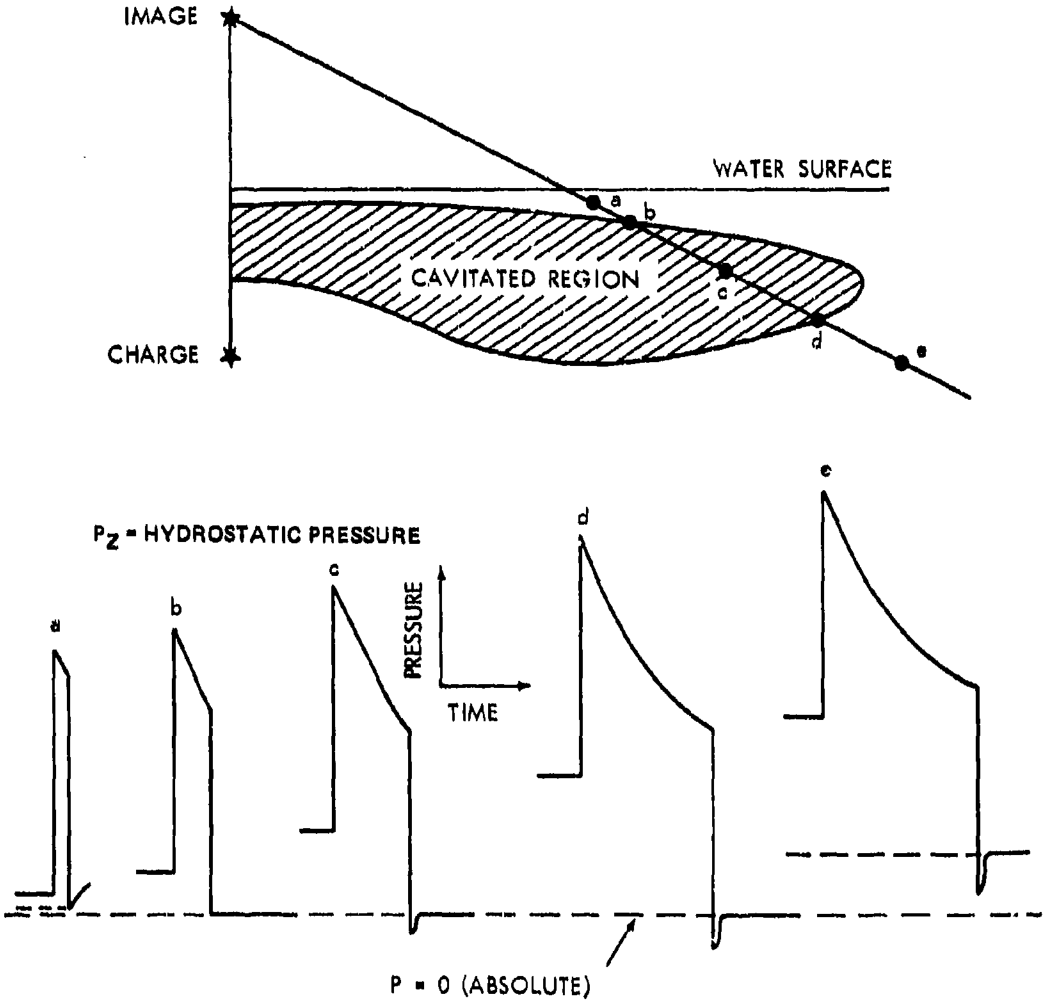

FIG. 1 WAVEFORMS AS MODIFIED BY CAVITATION (GASPIN AND PRICE, 1972)

(*Trinectes maculatus*) were included as non-swimbladder controls. To give a quantitative evaluation of fish damage, the numerical criteria of Hubbs, Schultz and Wisner (1960) were used (Table 1).

TABLE 1. DAMAGE CRITERIA

Damage Level	Criteria
(0)	No damage.
(1)	Only light hemorrhaging, principally in the tissues covering the kidney.
(2)	Gasbladder intact, but with light hemorrhaging throughout the body cavity, with some damage to the kidney.
(3)	No external indication of damage, but with the gasbladder usually burst. Hemorrhaging and organ disruption less extreme than in (4) and (5), but with gross damage to the kidney.
(4)	Incomplete break-through of the body wall, but with bleeding about the anus. The gasbladder is almost invariably broken and the other organs damaged as noted under (5).
(5)	Rupture of the body cavity. The break is usually a slit just to the side of the midventral line. Associated with this severe damage is a burst gasbladder and gross damage to other internal organs. The abdominal contents are often completely lost or homogenized.

3.5 Explosive Charges

3.5.1 The explosive charges used in the tests were pentolite spheres, manufactured in-house. The nominal charge weights were 1, 8, 31 and 68 pounds. The charges were centrally initiated by "Engineer's Special" detonators. This type of charge is commonly used in underwater explosions research.

4. Rigging and Instrumentation

4.1 Cages, Gages and Rigging

4.1.1 On each explosive test, there were five fish cage positions. At each position, there was a triplet of fish cages with a piezoelectric (PE) gage attached to the center cage. The fish cages were made of plastic mesh formed into

Hubbs, C. L., E. P. Shultz and R. L. Wisner, 1960, "Preliminary Report On Investigations of the Effects on Caged Fishes of Underwater Nitro-carbon-nitrate Explosions," Data Report, U. of California, Scripps Institution of Oceanography.

cylinders measuring about 20 inches in length and about 12 inches in diameter. The ends were reinforced by rings of 1/8" steel rod. One end was closed with the plastic mesh, and the other fitted with a circular door, made from the plastic mesh and reinforced with a steel ring around it's perimeter. The door was used to facilitate loading fish into the cage. The plastic mesh was chosen because its acoustic impedance is close to that of water, and therefore was not expected to interfere with the explosion pressure waves. The thin steel rod used for reinforcement was held to a minimum, in order to eliminate reflections.

4.1.2 The cages were mounted on a framework of thin steel rods in sets of three, parallel to one another, and touching along their long edges. They were mounted so as to lie in a horizontal plane, presenting their circular ends to the direction of the explosion. The individual cages were loaded with 10-20 specimens, one species to a cage. A triplet of cages, and the attendant framework, are shown in Figure 2.

4.1.3 A three-quarter inch PE gage was mounted on the end of the center cage facing toward the point of detonation. These relatively large gages sacrifice high frequency response in order to gain adequate signal levels at the fairly low pressure levels expected.

4.1.4 The gages were tourmaline piezoelectric gages manufactured in-house. Each gage was mounted on leads molded into an epoxy oil barrier. The leads were attached to a coaxial cable. The gage was sealed into a plastic tube filled with silicone oil. Research reported by Dempsey and Price (1972) indicates that this method of waterproofing affects the gage output less than any of the other methods tried.

4.1.5 To determine the relationship of the pressure history measured by the gage mounted outside the cage, to that actually occurring within the cage, a test was performed. A gage was mounted in its normal orientation on the exterior of the end of the center cage nearest the explosion. In addition, a gage was mounted in the center of the cage. The cages were then subjected to explosion pressures like those to be encountered in the actual test series. When the gage outputs were compared, there were no perceptible differences. Thus, the pressures measured in the fish tests are indicative of the actual pressures encountered by the fish.

4.1.6 The cage and gage assembly was suspended by 1/4-inch steel cables from an empty 55 gallon steel drum, which served as a float. The cages could then be suspended at any desired depth.

4.1.7 A total of five cage-gage assemblies were used on each shot, with from three to five horizontal standoffs. Where more than one depth was used at a given horizontal range, the lower cages were suspended from the ones above. The floats at different ranges from the charge were linked together by a steel cable, with small styrofoam floats spaced along the cable to keep it afloat. A sketch of the experimental array is shown in Figure 3.

Dempsey, J. B. and R. S. Price, 1972, "Reduction of Scatter in Underwater Shock Wave Measurements Made with Piezoelectric Gages," NOL Technical Report NOLTR 72-12.

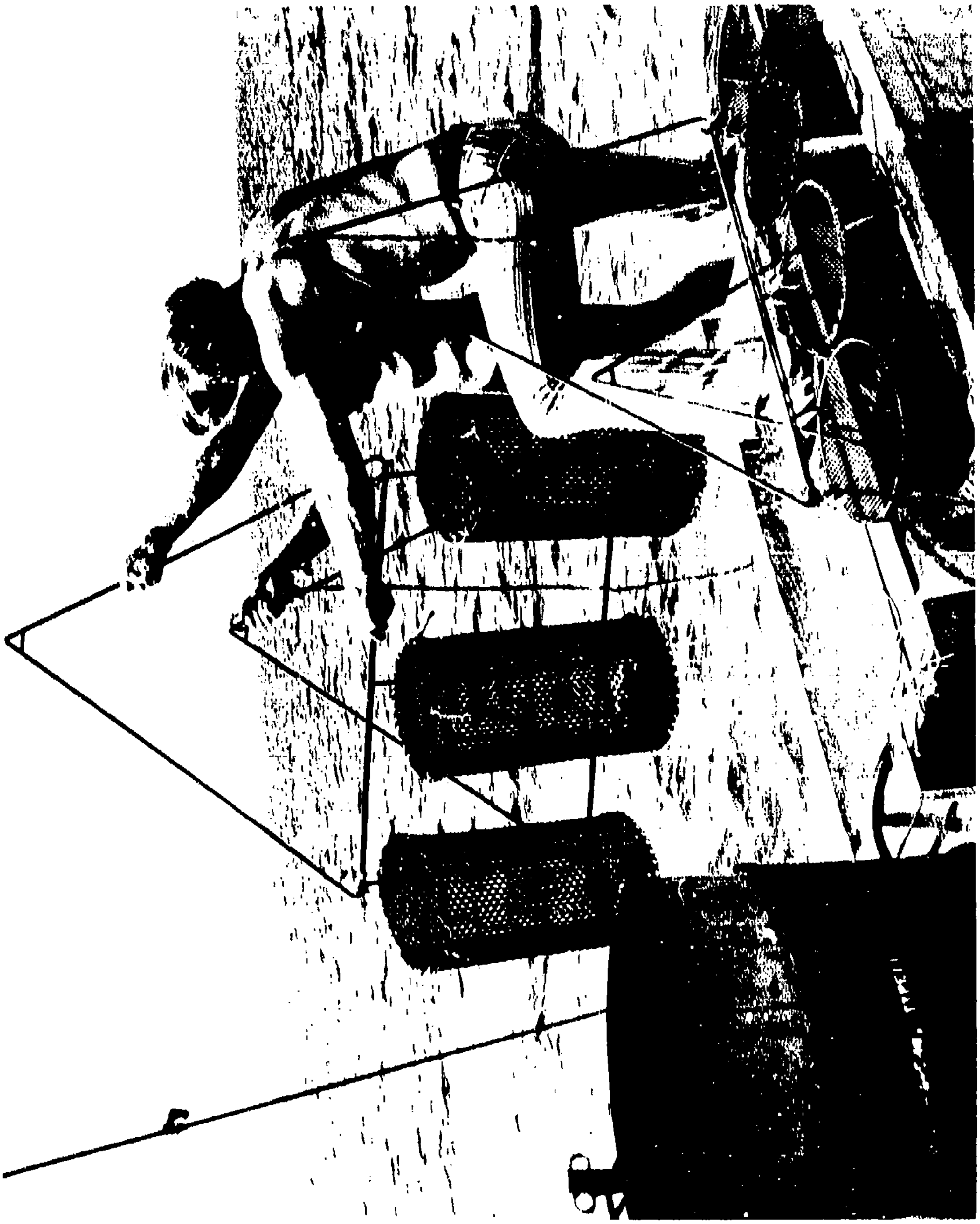

FIG. 2 CAGE TRIPLET AND SUPPORTING FRAMEWORK

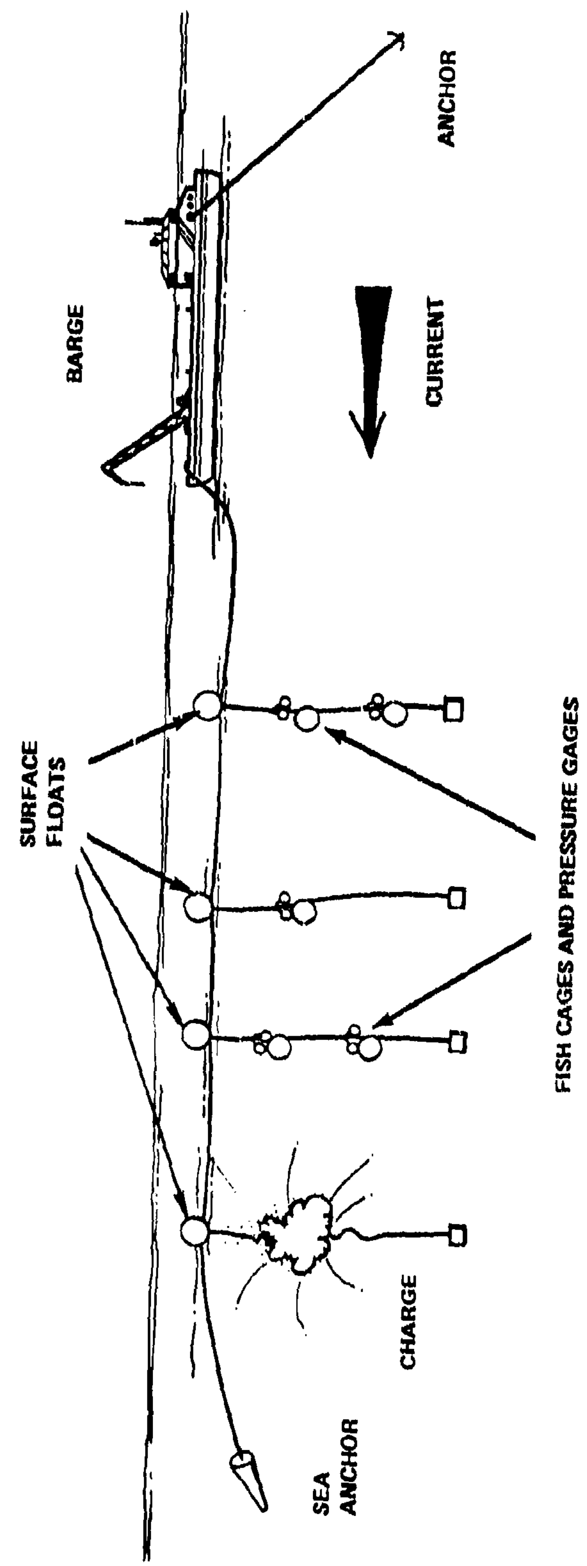

FIG. 3 TEST ARRAY

4.2 Recording System

4.2.1 The instrumentation for these tests consisted of five dual-beam oscilloscopes and a fourteen channel tape recorder. The signal from each gage was recorded at two gain settings on tape, and at low gain only on oscilloscope photographs.

4.2.2 The outputs of the five gages used on each shot were fed, by anti-microphonic coaxial cable, back to the instrumentation trailer on the deck of the Underwater Explosions Division barge. The cables were terminated in surge resistors and standard capacitors connected to high input impedance amplifiers, that preceded the oscilloscope inputs. The "Q-Step" method of calibration as described by Cole (1948) was used.

4.2.3 The gage outputs were recorded on the second channels of five dual beam oscilloscopes. The second trace sweeps were set to trigger internally on the arrival of the shock front at each gage. The scopes were kept from triggering on the firing pulse, and noise prior to the shock arrival, by operating in the "triggerable after delay" mode. The first channel of each oscilloscope was connected in parallel with its second channel, but was set for a higher gain with its intensity turned off, and was not photographed as was the second trace. This was done to provide dual gain for each gage recorded by the tape recorder. The vertical amplifiers of the oscilloscopes acted as pre-amplifiers for the FM tape recording. The five second-trace vertical outputs were connected directly to the input of the Ampex FR-1900 tape recorder. The first-trace vertical outputs were set at a high gain to better resolve the small amplitude negative pressures in the signal. In order to prevent system overload by the much higher positive amplitudes, the high gain signals were fed through a circuit which clipped off the high positive pressure of the shock wave before it reached the tape recorder.

4.2.4 The oscilloscopes used were Tektronix type RM 565, with 2A63 vertical amplifiers. The frequency response exceeded 300 kHz, with a rise time of less than 1 μsec. The data were photographed with Tektronix C-12 cameras, using Polaroid type 47 film.

4.2.5 The Ampex FR-1900 tape recorder was run at 60 ips, on the FM intermediate band, yielding a frequency response of 20 kHz. The data were retrieved in the field on a Honeywell Visicorder.

4.3 Underwater Photography

4.3.1 In addition to the pressure instrumentation, one station on each shot was instrumented for underwater photography. The camera was installed beneath a triplet of cages, pointing up, toward the water surface. This orientation made use of the natural light. To supplement the natural illimination, four electric lights were used. Figure 4 shows a camera station ready to be lowered into the water.

5. Field Operations

5.1 The Test Site

5.1.1 The tests were carried out in the Chesapeake Bay. In order to minimize perturbations due to the bottom, we used the deepest point of the bay.

Cole, R.H., 1948, Underwater Explosions, Princeton University Press, Princeton, New Jersey.

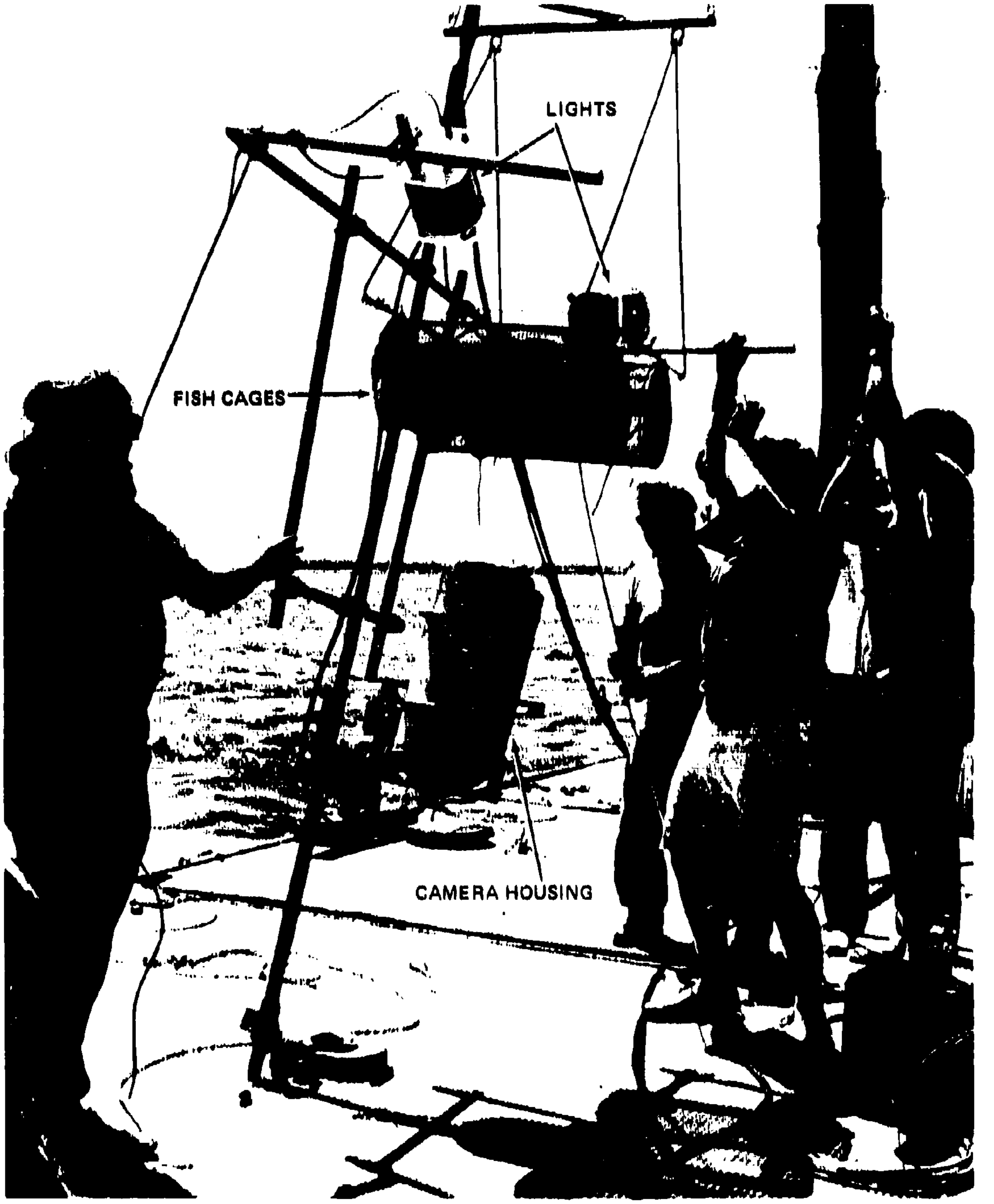

FIG. 4 CAMERA STATION

The water depth was ~150 feet in all shots. An unusual feature of the test site was the character of the bottom reflected shock wave. Typically, bottom reflections from a hard bottom are of positive polarity. At this test site, the bottom was such that the shock wave underwent an 180° phase shift upon reflection, thereby giving a negative reflection, much like that from the surface. As reported by Walker and Gordon (1966), who did an experiment at this same site, the bottom gives rise to a second cavitation front, beginning near the bottom and extending up toward the surface.

5.1.2 All operations were conducted from the deck of an 80 x 22 foot, self-powered barge. In most instances, the rig was deployed by using a sea anchor to pull out the rigging from the barge, following the direction of flow of the tide. Following the sea anchor, the charge and its supporting float were launched.

5.2 Biological Specimens

5.2.1 Much of the following discussion of the handling of biological specimens follows that of Wiley and Wilson (1974). Their report is reproduced as Appendix B to the present one.

5.2.2 The biological specimens were netted by the CBL research vessel Orion. Fresh specimens were obtained just prior to the beginning of explosive operations, and several times during the operations, so that all fish used were judged to be in good condition. Fish were collected from the Patuxent River in the vicinity of Solomons Island using a 25-foot semi-balloon otter trawl, with a 1/2-inch stretch mesh liner. The fish selected for use in the experiments were sorted out by hand, and placed in a 275-gallon tank supplied with flowing river water. The tank was transferred from the Orion to the deck of the test barge, where the fish were kept until needed. The holding tank was supplied with running water from the bay, and compressed air was blown into the tank through wooden diffusers to keep the water well oxygenated.

5.3 Since mortality due to stresses caused by handling and capture usually occurred within several hours, fish were generally held at least one day before being used in an experiment.* In this way the specimens were given time to adapt to captivity. In the course of the explosive tests, the fish were lowered rather quickly to depth in the water, and given about 1/2 to 1 hour to adapt to their depth. It is not known how long our test species require to adapt to a given depth (up to 40-feet in our tests), after being kept in a shallow tank for some days. Consequently, we do not know if the test fish were operating at neutral bouyancy.

5.2.3 As fish were needed for a particular test, they were hand netted and transferred to a bucket of water. When the bucket held all the specimens for an individual cage, they were carefully poured into a cage which was standing

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Walker, R. R. and J. D. Gordon, 1966, "A Study of the Bulk Cavitation Caused by Underwater Explosions," David Taylor Model Basin Report 1896.
Wiley, M. L. and J. S. Wilson, 1974, "Final Report: Environmental Effects of Explosive Testing," U. of Maryland, Natural Resources Institute, Chesapeake Biological Laboratory, Ref. No. 74-9. (Unpublished Manuscript)
*The exception to this is shot #519, for which the fish were netted only a few hours before the test.

upright in a holding box supplied with running water. The cage door was then fastened, and the cage was immediately placed over the side, to be promptly affixed to the rigging. The sea anchor was allowed to pull the rig out, following the direction of flow of the tide. Due to this method of placement, the current always flowed through the fish cages in the direction of the charge. In order to maintain their positions in the cages, the fish were forced to swim against the current. This resulted in all specimens being tail-on to the explosion. When all measurement stations were in place, and the rig line was pulled out straight from the barge, the charge was fired.

5.2.4 After the explosion, the rig was pulled back onto the barge. The fish from individual cages were placed in tagged plastic bags and immediately put on ice. The specimens were dissected, and their damage assessed, usually within an hour of the test. The damage classifications are given in Section 3, above. Some specimens were left in their cages and placed back in the holding tank for further observation prior to dissection. A more detailed account of the handling of specimens is given in Appendix B.

5.2.5 On the weekend preceding the beginning of explosive operations, the air supply to the holding tank was inadvertantly cut off. Because of this, most of the white perch in the tank died. The spot and hogchokers were judged to be in good condition. The first explosive test (shot #517) had only a minimal number of white perch, and the second (#518) had none. After this, our fish supply was replentished.

5.2.6 The water conditions were monitored just prior to most of the shots. Temperature, salinity, conductivity, and dissolved oxygen content were measured as a function of depth. A typical sound speed profile constructed from these data is shown in Figure 5. A ray tracing program run with this profile indicated that no significant refractive effects were to be expected in our tests.

5.2.7 During the hot summer months, a lack of dissolved oxygen is to be expected at depth. Information available during the planning of these tests led us to expect that there would be sufficient oxygen to support fish life at depths down to about 40 feet. When actual measurements were made at the test site, however, we found sufficient oxygen only down to about 20 feet. These measurements were confirmed by placing control specimens down below this depth for a period of one hour. They showed 100% mortality. Due to this, test specimens were generally limited to depths of 20 feet or less. In the later stages of the experiment, some specimens were placed deeper than 20-feet. Such data are judged to be somewhat dubious, as the specimens were probably dead before the shot. Death from asphyxiation can be differentiated from death due to explosion damage, upon dissection. These deeper data points do, therefore, have some value. The lack of reliable deep data points represents one of the fundamental limitations of this test series.

5.3 Field Playouts

5.3.1 Immediately after each shot, the oscilloscope pictures were developed, and preliminary Visicorder playouts of the magnetic tape data were made. From these, a running check of the results was made. Due to an error in the operation of the tape recorder, the data for one shot (#524) was lost. For this shot, only the field playouts exist.

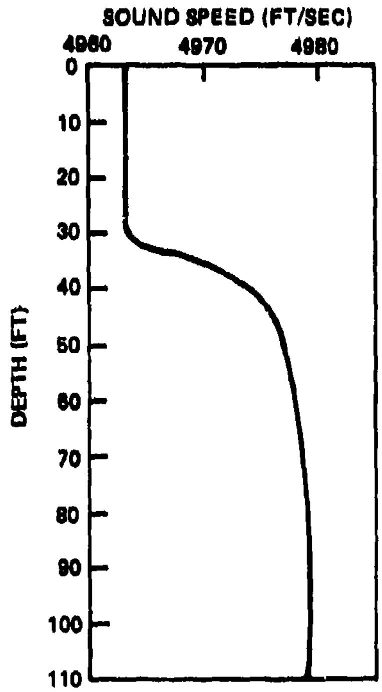

FIG. 5 CHESAPEAKE BAY SOUND SPEED PROFILE

6. Data

6.1 A total of 11 explosive shots were fired in our tests against swim-bladder fish. The test conditions are given in Table 2, below. On this series, 39 successful oscilloscope records were obtained, giving good high frequency resolution of the shock waves. A total of 45 low gain tape records were obtained, with 40 of these being available for digital analysis, and give a good representation of the entire pressure history. The high gain tape channels yielded 50 records, giving good resolution of the negative (relative to ambient) pressure phases. These high gain records are believed to give the best representation of such pressures that have been obtained to date. Of a total of 165 possible data records (11 shots, 5 scope records and 10 tape records per shot) we obtained 134 good records.

6.2 The records are generally of good quality with a high signal-to-noise ratio. Appendix C contains plots of all the low gain tape records which were digitized.

6.3 The oscilloscope records were read by hand, to yield the peak over-pressure of the shock wave, as these give more accurate results than the tape records (due to the lower frequency response of the tape recorder). A summary of these data is shown in Figure 6. For this series of tests, the peak pressure was found to be given by the function

$$P_{max} = 2.46 \times 10^4 \left(\frac{W^{1/3}}{R}\right)^{1.13}$$

where W is the charge weight in pounds, and R is the slant range in feet. This function indicates a peak pressure ∿5% higher than the accepted value for pentolite. The peak pressure data exhibit a standard deviation of ∿7% from the function, which is considered good for this type of data.

6.4 The times of significant events were obtained from paper playouts (Visicorder) of the tape records, which included time code. The high gain records were read to obtain values of the plateau pressure. The low gain records were digitized and analyzed on a CDC 6400 computer to yield values of secondary pressures and integrated quantities (impulse and energy) as a function of time.

6.5 The biological data comprises the evaluation of 693 spot, 481 white perch and 370 hogchokers. For each specimen, the total length was recorded, and the damage sustained was evaluated, according to the numerical criteria given in Section 3, by dissection.

6.6 Upon consultation with the biologists on the project, it was decided that a damage level of two or higher would be taken as lethal damage. Few of the fish that sustained this level of damage were killed outright, and many of them probably would have survived if allowed to recuperate in a protected environment (see Appendix B). Under normal circumstances, however, fish with significant damage would be likely victims of predators. Consequently, for purposes of this study, this modest damage level was chosen as a conservative indicator of likely mortality.

TABLE 2: Summary of Data
(Key to symbols on next page)

SHOT #	W	DOB	CH	H	D	P_{MAX}	I	E ($\times 10^5$)	CAV	ΔP_1	Δt	% of Fish with Damage Level ≥ 2 SPOT	WHITE PERCH
517	1	5	4	42	5	311	37.8	1.87*	Yes	65	.38	100	100
			6	42	20	321	50.3	1.82	No	39	.98	100	100
			8	118	5	100	7.2	.151	No	--	.20	0	0
			10	118	20	104	13.8	.228	No	32	.43	0	0
			12	190	5	64	2.6	.0371	No	+	.15	0	0
518	8	20	4	82	5	363	86.5	4.62	Yes	80	.80	100	--
			6	82	20	415	--	--	No	59	--	100	--
			8	250	5	107	14.3	.314	Yes	36	.33	100	--
			10	380	20	71	18.2	.221	No	38	.65	100	--
			12	380	10	75	11.1	.154	No	50	.33	90	--
519	8	40	4	82	5	--	--	--	Yes	--	--	100	100
			6	82	20	267	101.	2.88	Yes	45	3.8	100	100
			8	250	5	86	23.5	.433	Yes	40	.50	100	100
			10	380	20	55	23.0	.181	No	23	1.3	0	0
			12	380	10	69	15.0	.173	Yes	34	.58	100	0
521	31	30	4	125	10	360	--	--	Yes	80	--	100	100
			12	370	5	121	18.4	.459	Yes	104	.30	100	0
			6	370	18	116	34.4	.681	Yes	53	.70	100	91
			8	580	10	--	--	--	--	--	--	55	0
			10	678	10	64	9.2	.140	Yes	+	.25	5	0
522	31	30	4	125	10	388	--	--	Yes	--	--	100	100
			12	370	5	125	17.2	.466	Yes	90	.32	86	0
			6	370	18	105	34.0	.702	Yes	45	.65	100	100
			8	580	10	60	9.1	.128	Yes	40	.50	68	0
			10	700	10	69	8.5	.137	Yes	29	.28	0	0
523	31	15	4	125	10	343	112.	7.01	Yes	118	.75	100	100
			12	370	5	99	8.5	.205	Yes	78	.20	76	0
			6	370	18	129	23.7	.600	Yes	65	.38	100	50
			8	580	10	--	--	--	--	--	--	40	0
			10	700	10	40	4.6	.0268	Yes	13	.53	30	0
524	68	40	4	170	10	382	--	--	Yes	86	1.00	100	100
			12	500	10	118	--	--	Yes	86	.27	86	0
			6	500	18	111	--	--	Yes	60	.48	75	20
			8	500	40	83	--	--	No	46	1.28	100	80
			10	780	10	61	--	--	No	+	.15	80	10

*That is, 1.87×10^5 ergs/cm^2 +anomolous waveform — No Data

TABLE 2: Summary of Data
(CONT'D)

SHOT #	W	DOB	CH	H	D	P_{MAX}	I	E (x10^5)	CAV	ΔP_1	Δt	% of Fish with Damage level ≥ 2: SPOT	WHITE PERCH
525	68	70	4	170	10	346	157.	7.26	Yes	89	1.55	100	100
			12	500	10	104	35.9	.814	Yes	107	.60	100	---
			6	500	18	113	47.7	.855	Yes	51	1.00	100	70
			8	500	40	91	65.7	.897	No	83	2.38	100	60
			10	780	10	62	17.0	.259	Yes	62	.43	100	20
529	1	20	4	110	40	119	35.4	.417	No	30	2.93	91	0
			6	190	5	68	6.1	.0840	Yes	32	1.30	0	0
			8	190	30	62	13.4	.0909	No	16	.23	9	0
			10	262	5	37	4.6	.0416	No	20	.93	0	0
			12	262	30	43	9.1	.0419	No	13	.27	0	0
530	1	40	4	110	40	123	40.7	.364	No	16	5.35	0	10
			6	190	5	69	10.1	.0963	Yes	19	2.53	11	0
			8	190	30	71	16.2	.117	No	14	.38	10	0
			10	262	5	42	5.5	.0379	No	23	1.83	0	0
			12	262	30	43	11.6	.0549	No	10	.47	10	0
531	8	40	4	250	10	111	22.4	.339	Yes	36	.70	70	100
			12	315	10	75	14.4	.181	Yes	35	.50	29	7
			6	380	10	68	14.0	.217	No	36	.35	60	0
			8	540	10	46	6.4	.057	No	33	.38	30	0
			10	760	10	29	7.2	.033	No	23	.68	0	0

W = Charge Weight (lb)
DOB = Depth of Burst (ft)
H = Horizontal Range (ft)
D = Cage Depth (ft)
P_{MAX} = Peak Overpressure (psi)
CH = Channel #
I and E were integrated from the time of shock wave arrival to the time of surface reflection arrival

I = Shock Wave Impulse (psi msec)
E = Shock Wave Energy (ergs/cm^2)
CAV : was cavitation observed?
ΔP_1 = Drop in pressure at surface reflection arrival (psi)
Δt = Shock wave duration (msec), i.e., time after shock arrival at which surface reflection arrived.

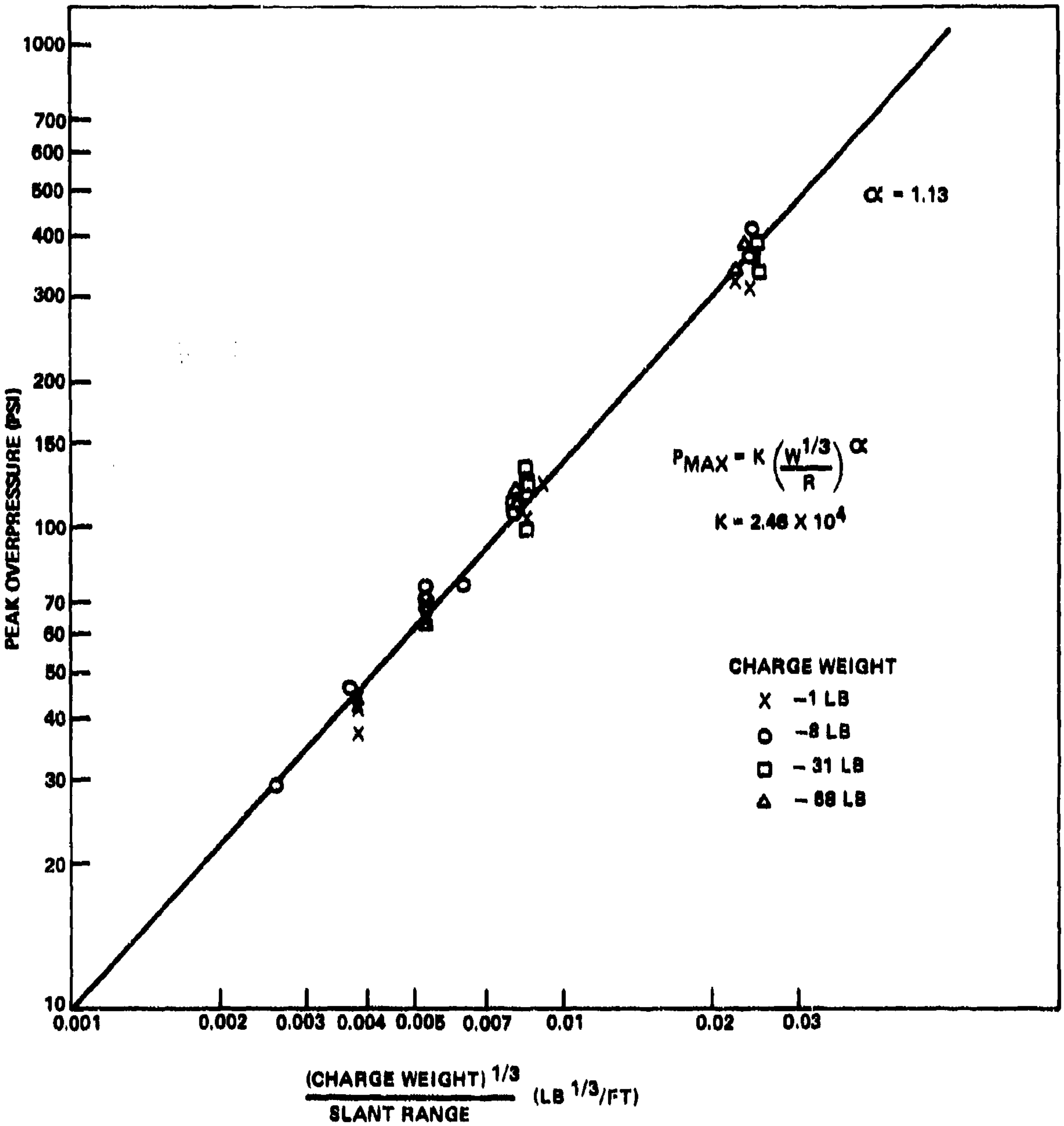

FIG. 6 SUMMARY OF OSCILLISCOPE PEAK PRESSURE DATA

6.7 The biological data show a strong internal consistency. When lethal damage (i.e. damage level ≥ 2) occurred at a given station, to a given species, the tendency was for all fish of that species to receive lethal damage at that station. In all, 76 out of the 106 total fish cages used for spot and white perch had a percent mortality of 0% or 100%. This tendency toward "all or nothing" mortality is at odds with the gradual sigmoid dose--response curve to be expected in biological tolerance data.

6.8 Successful underwater motion pictures of one cage position was obtained on each shot.

6.9 The findings of the preliminary analysis of these data are given in the next section.

7. Preliminary Results

7.1 Swimbladder Versus Non-Swimbladder Fish

7.1.1 In the course of our tests, only one of our hogchoker "controls" was found to have experienced as much as damage level one. It is clear that this type of fish is highly resistant to explosion damage. Since hogchokers were uninjured at positions where spot and white perch were receiving heavy damage, and the major physiological distinction between these is the swimbladder, our data indicate that swimbladder fish are, indeed, much more vulnerable to explosions than those lacking swimbladders. This is in agreement with information in the literature. Hogchokers will be eliminated from further discussion. We will now examine various simple shock wave parameters for correlation with fish damage.

7.2 Correlation of Damage With Peak Pressure

7.2.1 Peak shock wave overpressure is the most commonly suggested explosion parameter to be related to fish damage. Figures 7 and 8 show our results for spot and white perch respectively. Below 130 psi, there is no clear pattern in either case. The onset of heavy lethality occurs at about 20-40 psi. From here, up to 130 psi, we see mainly scatter. There is little indication of increasing mortality with increasing peak pressure.

7.2.2 For spot, there is some indication that above about 80 psi, high mortalities are likely. There are several data points at peak pressures over 100 psi, however, which indicate no damage. Above 240 psi, there are 100% fatalities.

7.2.3 The white perch data show no increase in mortality with increasing peak pressure between 60 and 130 psi. Above 240 psi, as with the spot, there are 100% mortalities.

7.2.4 The data give little reason to consider peak pressure a good criterion on which to base estimates of fish lethality. This is fairly obvious below 130 psi. Because there were no data gathered between 130 and 240 psi, and all specimens subjected to greater than 240 psi were killed, it is tempting to conclude that at some point between 130 and 240 psi, there is a peak pressure which causes certain lethality. This may not be justified. Due to the limited data set at hand, and particularly due to the limited depth range of the specimens,

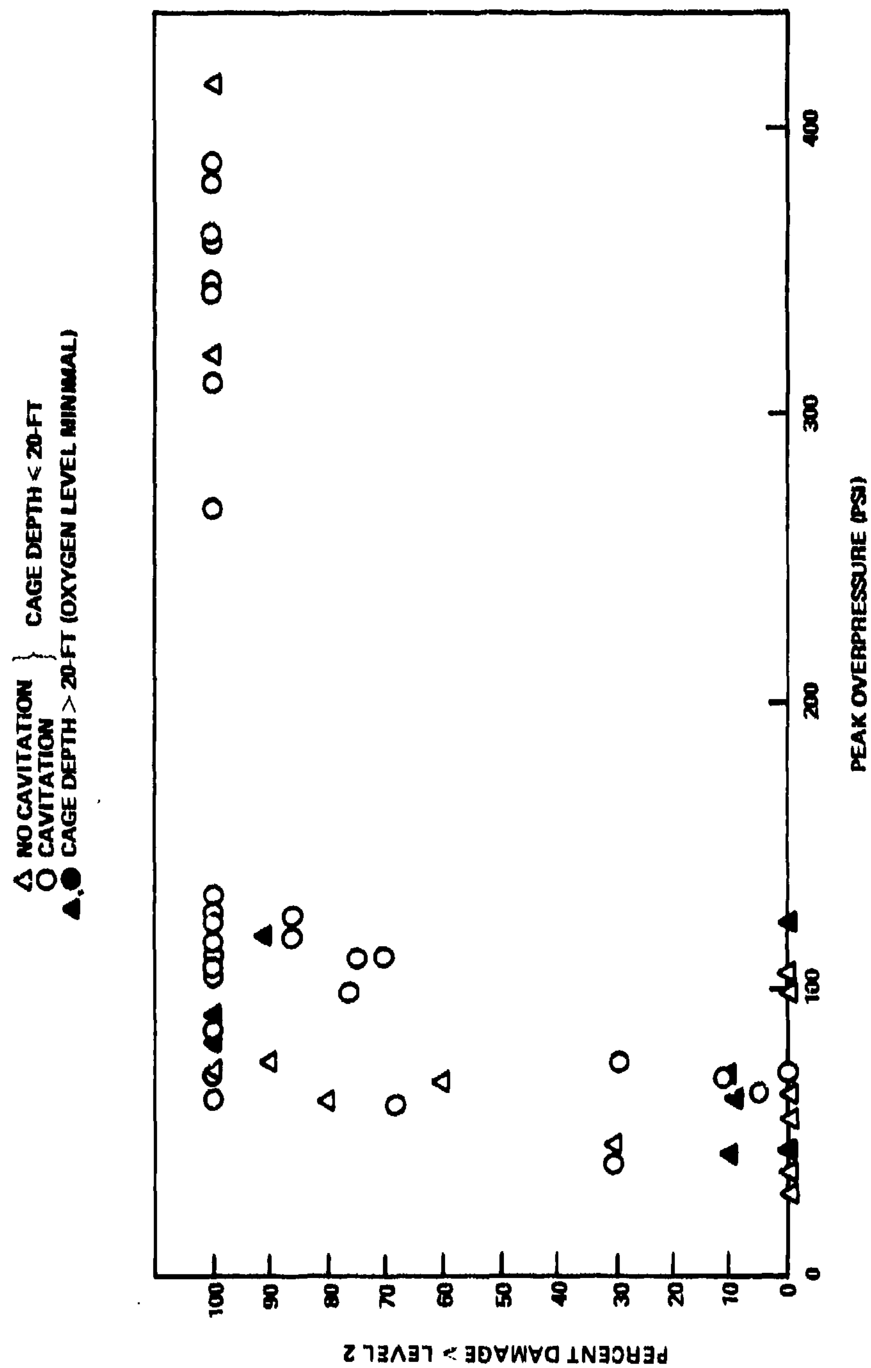

FIG. 7 SPOT DAMAGE VS PEAK OVERPRESSURE

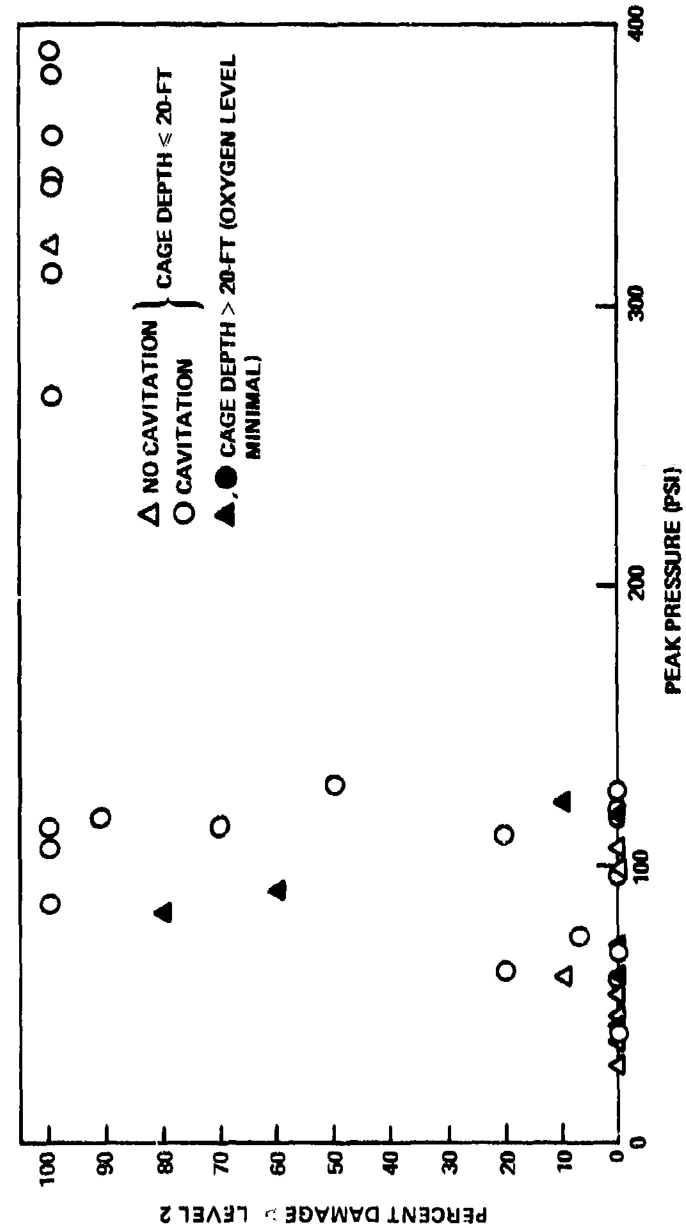

FIG. 8 WHITE PERCH DAMAGE VS PEAK OVERPRESSURE

high values of peak pressure tend to correlate quite strongly with high values of other explosion parameters. Thus a data point with high peak pressure tends to also have high values of impulse and energy, and tends to be in the cavitated region as well. In the absence of a good analytical model of the damage process, we cannot conclude from these data that peak pressure alone is a primary component in fish damage.

7.3 Cavitation and Negative Pressures

7.3.1 Unusual local conditions at the test site caused the bottom reflected shock wave to have negative polarity. This tended to generate a second cavitation front, beginning near the bottom and traveling upward. We have no accurate way of predicting the cavitated zone from a negative bottom reflection. Consequently, cavitation occurred at many more cage locations than had been anticipated. A typical set of P-E records, taken within the cavitated region, is shown in Figure 9. The two traces are from the same gage. The upper trace shows the pressure history in full detail. The lower is the clipped, high gain record, showing the details of the negative excursions. At the time of surface reflection arrival, the total pressure reaches absolute zero. This can be more accurately determined on the lower trace. The pressure remains at absolute zero until closure occurs, and then gradually returns to the original ambient pressure. At a still later time, the bottom reflected shock wave arrival also causes the total pressure to reach absolute zero, and the water cavitates again.

7.3.2 The cavitated region for each shot geometry was predicted by the method of Gaspin and Price (1972). These predictions were for cavitation caused by the surface reflected shock wave. Agreement was good between the measured data and these predictions. In 46 of 53 cases, theory and data agreed on the existance of cavitation at a given point. In all seven cases where there was disagreement, cavitation was predicted but not observed. A possible explanation for the observed cavitated region to be smaller than predicted involves the mathematical modeling of the shock wave. Gaspin and Price used an exponential to represent the shock wave. This tends to predict a too low pressure in the tail of the shock wave. As a consequence, the negative surface reflection encounters a lower residual shock wave pressure in the model than in reality. In some instances, this would enable the pressure to reach absolute zero in the model, when the prototype does not. This would lead to a prediction of a larger cavitated region than is observed.

7.3.3 It is clear from the data that the lethal zone for swimbladder fish cannot simply be equated to the cavitated region. No correlation was found between cavitation and fish mortality for either spot or white perch. In Figures 7 and 8, for spot and white perch, the circles indicate those points at which cavitation occurred. Cavitation originating from the surface and from the bottom are not differentiated. There is no particular pattern evident to indicate cavitation as being important in the fish damage results reported here. As a consequence of the bottom generated cavitation front, there are many more data points in the cavitated region than outside it, particularly at high peak pressures.

7.3.4 Although cavitation per se must be ruled out as the governing parameter in swimbladder fish damage, negative pressure is clearly important. The nature of the injuries found in our specimens seems indicative of overexpansion. The limit of underpressure amplitude is governed by hydrostatic pressure. As a consequence of this, combined with our limited range of cage depths, we have only a

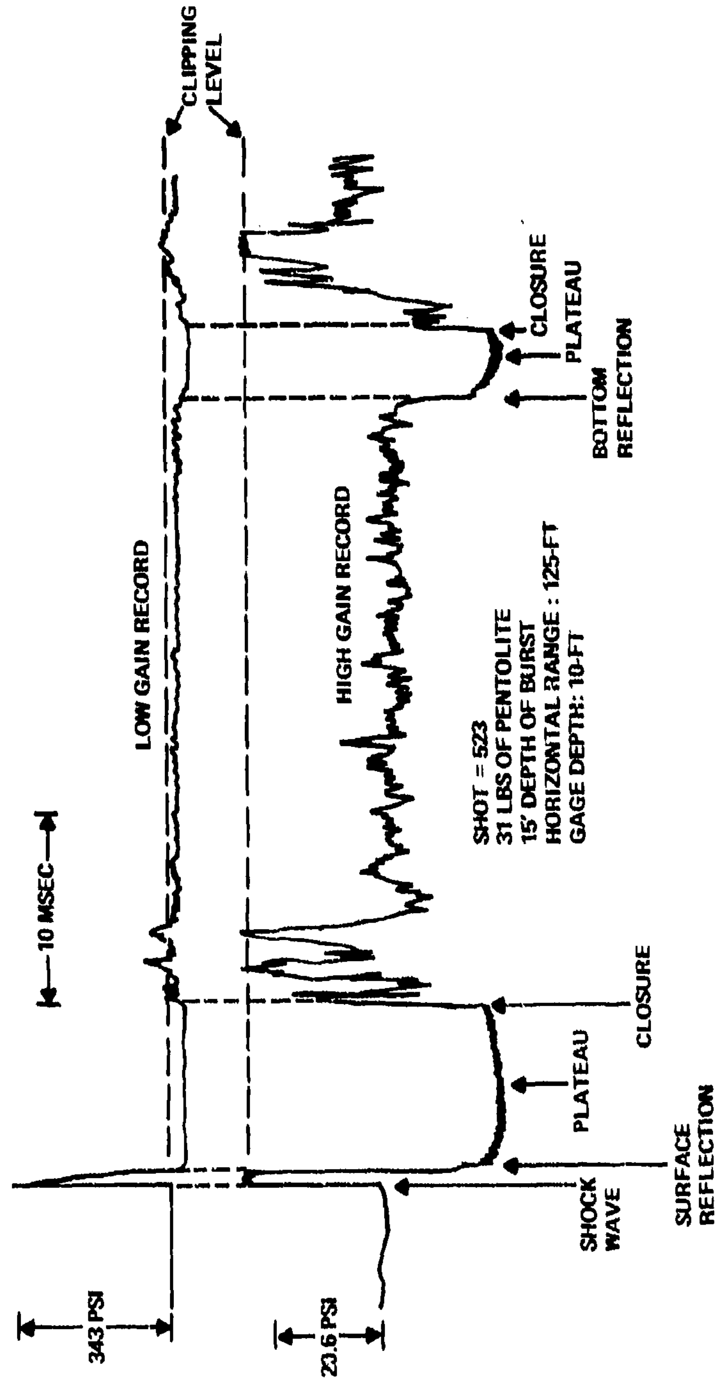

FIG. 9 LOW GAIN AND HIGH GAIN PRESSURE–TIME RECORDS

small variation in underpressure represented in our data. Rather than underpressure alone, the total pressure drop was examined for possible correlation with damage.

7.3.5 A measure of the actual tension experienced by the fish is the drop in pressure at the time of surface reflection arrival. At the time of arrival of the shock wave, the fish undergoes considerable compressive force. After a short interval, the positive pressure is suddenly cut off, and the total pressure drops below hydrostatic. In the cavitated region, the total pressure drops to near absolute zero. The relative tension experienced by a specimen may be indicated by the difference between the residual pressure in the tail of the shock wave at the time of surface reflection arrival, and the "plateau" of the underpressure phase. This pressure drop is shown as ΔP_1 in Figure 10. This figure shows the percent mortality for spot versus ΔP_1. For values of ΔP_1 below 35 psi, all mortalities are 10% or lower. There is a rapid increase in damage for ΔP_1 between 35 and 40 psi, and above 40 psi, all mortalities are 75% or more. The mortality rate for spot is seen to be strongly related to the pressure drop at the time of surface reflection arrival.

7.3.6 Figure 11 shows the white perch percent mortality plotted against ΔP_1. Obviously, for this second fish species tested, there is no correlation with ΔP_1 similar to that for the spot data.

7.4 Impulse and Energy

7.4.1 Shock wave impulse has been identified as an important parameter in damage to many species of animals (Richmond, et al (1973)). Our mortality data for spot and white perch are plotted against shock wave impulse in Figures 12 and 13. Figures 14 and 15 show percent mortalities for each species plotted against shock wave energy. No clear correlations are present in any of these. The correlation between white perch mortality and shock wave energy seems somewhat better than the others, but is not convincing proof of a causal relationship.

7.4.2 As yet unpublished data, gathered elsewhere, have indicated a strong correlation of severe fish damage with shock wave impulse. These data were gathered with all fish and charges at depths of ten feet and less. A subset of our data was constructed to match these restrictions as closely as possible. Figure 16 shows the percentage of spot experiencing damage level 3 and worse for all cases in which the fish were at a depth of 10 feet or less, and the charge depth was a maximum of 20 feet. Below $\sim$7 psi·msec, there is no damage. Above that level, there is a consistent, monotonic increase in percent damage with increasing shock wave impulse. The conclusion that shock wave impulse is associated with severe damage, for shallow fish and shallow explosions, is, therefore, supported by our data. This cannot be extended to deeper data.

7.5 Duration of the Shock Wave

7.5.1 In a current analytical study, to be reported elsewhere (Goertner (1975)), the dynamics of a swimbladder oscillating under the influence of the underwater explosion pressure field is being investigated. The study indicates that the phase

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Richmond, D.R., J.T. Yelverton and R.E. Fletcher, 1973, "Far-Field Underwater Blast Injuries Produced by Small Charges," Defense Nuclear Agency Report DNA 3091T.

Goertner, J.F., 1975 "Mortality of Fish Subjected to Underwater Explosions: Correlation of Observed Damage with the Dynamical Motion of the Gas Bladder," private communication

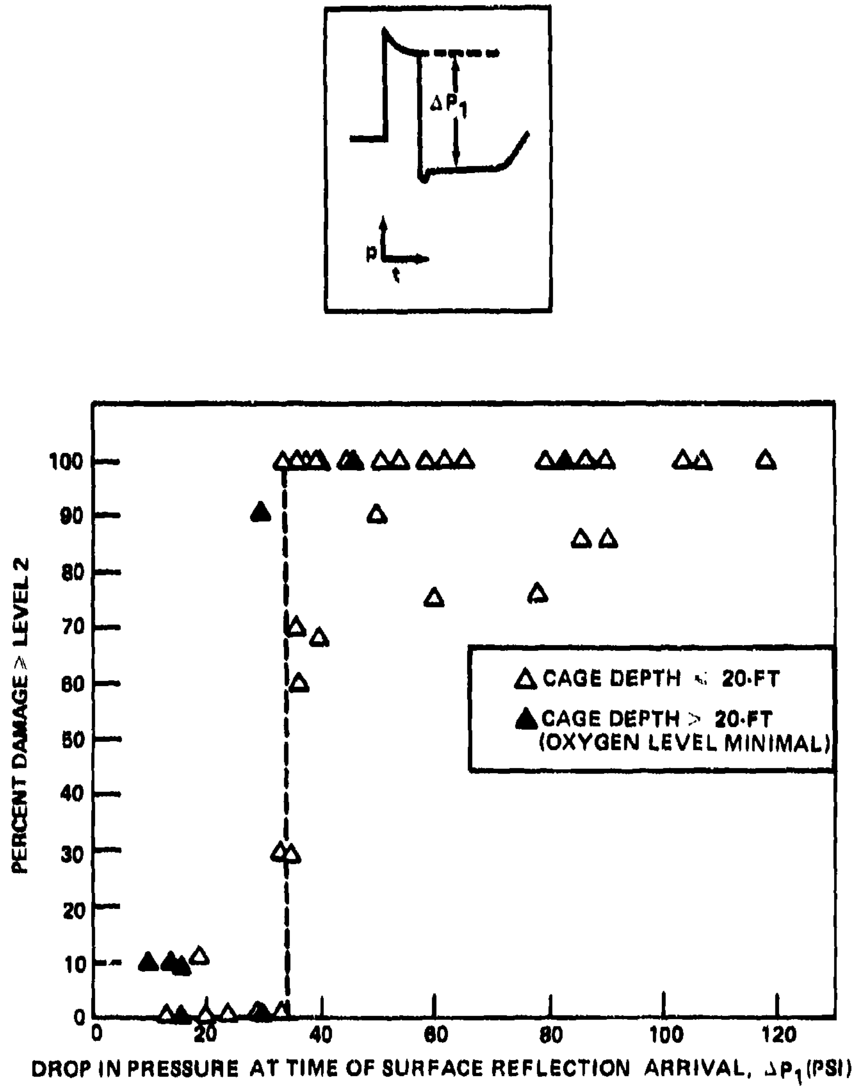

FIG. 10 SPOT DAMAGE VS DROP IN PRESSURE AT TIME OF SURFACE REFLECTION ARRIVAL, ΔP_1

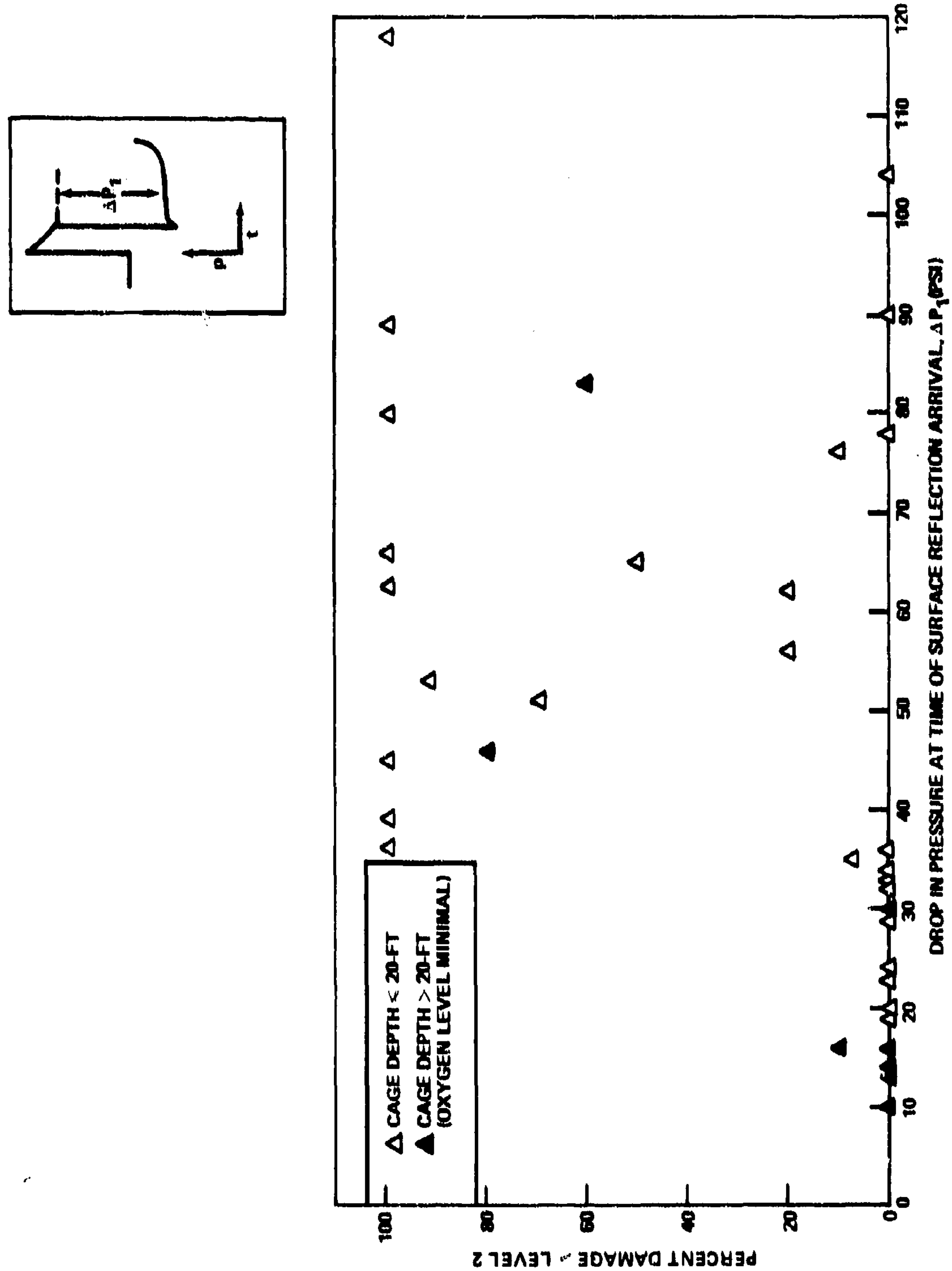

FIG. 11 WHITE PERCH DAMAGE VS DROP IN PRESSURE AT TIME OF SURFACE REFLECTION ARRIVAL, ΔP_1

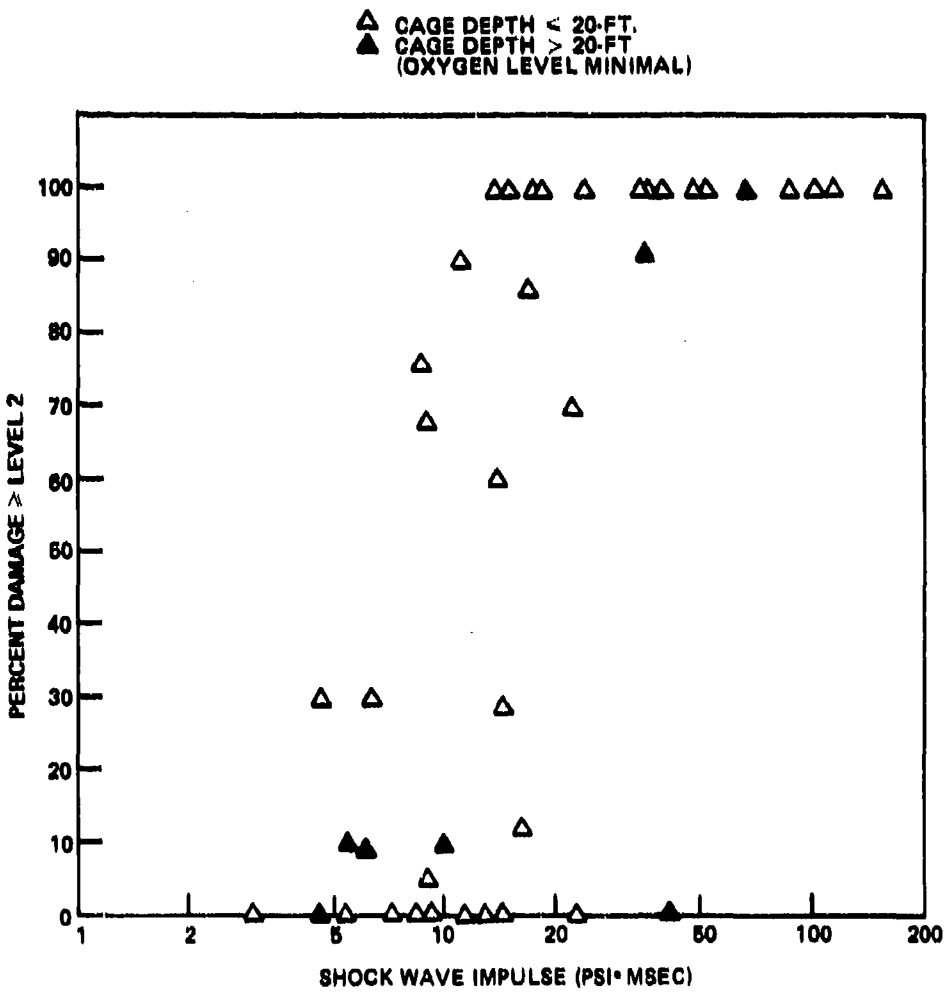

FIG. 12 SPOT DAMAGE VS SHOCK WAVE IMPULSE

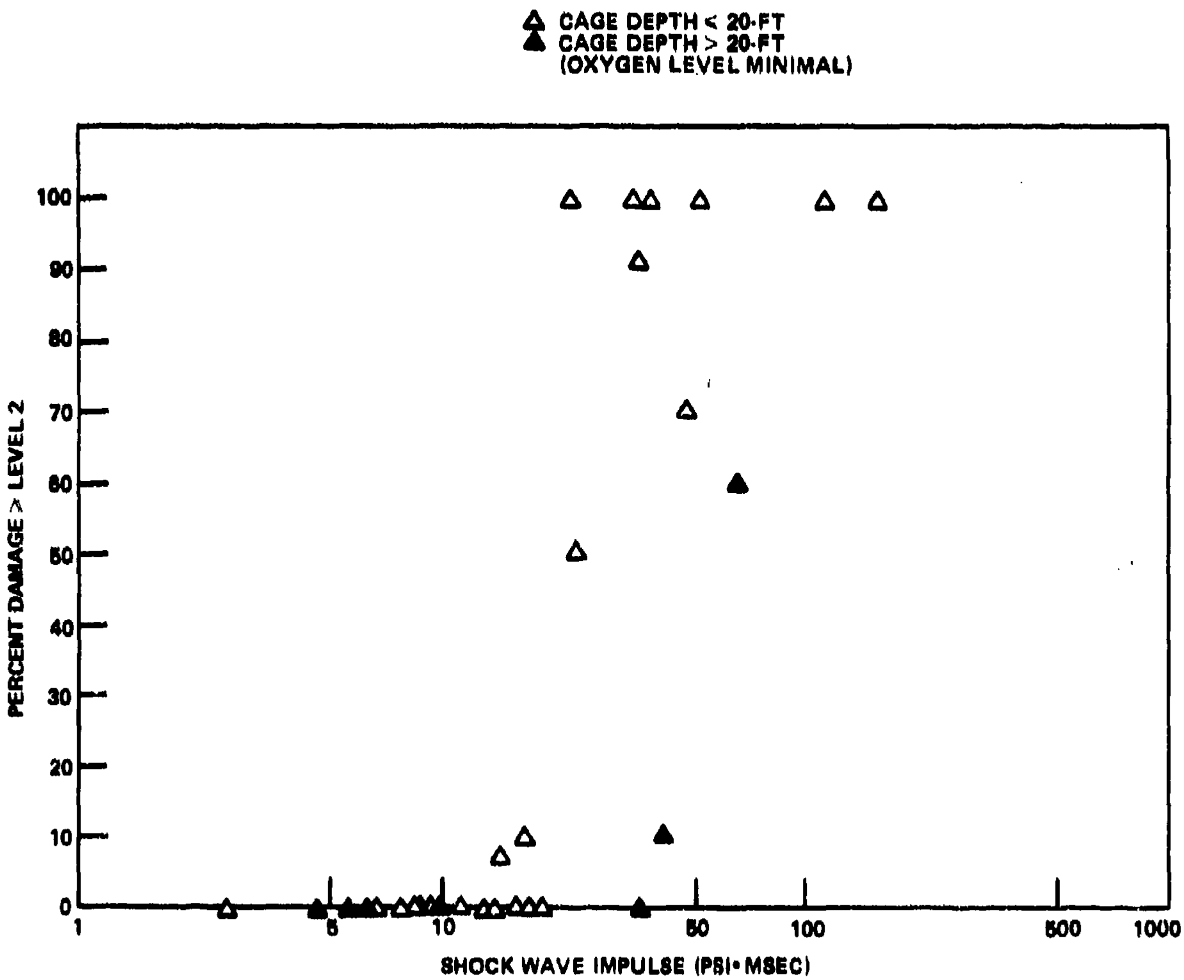

FIG. 13 WHITE PERCH DAMAGE VS SHOCK WAVE IMPULSE

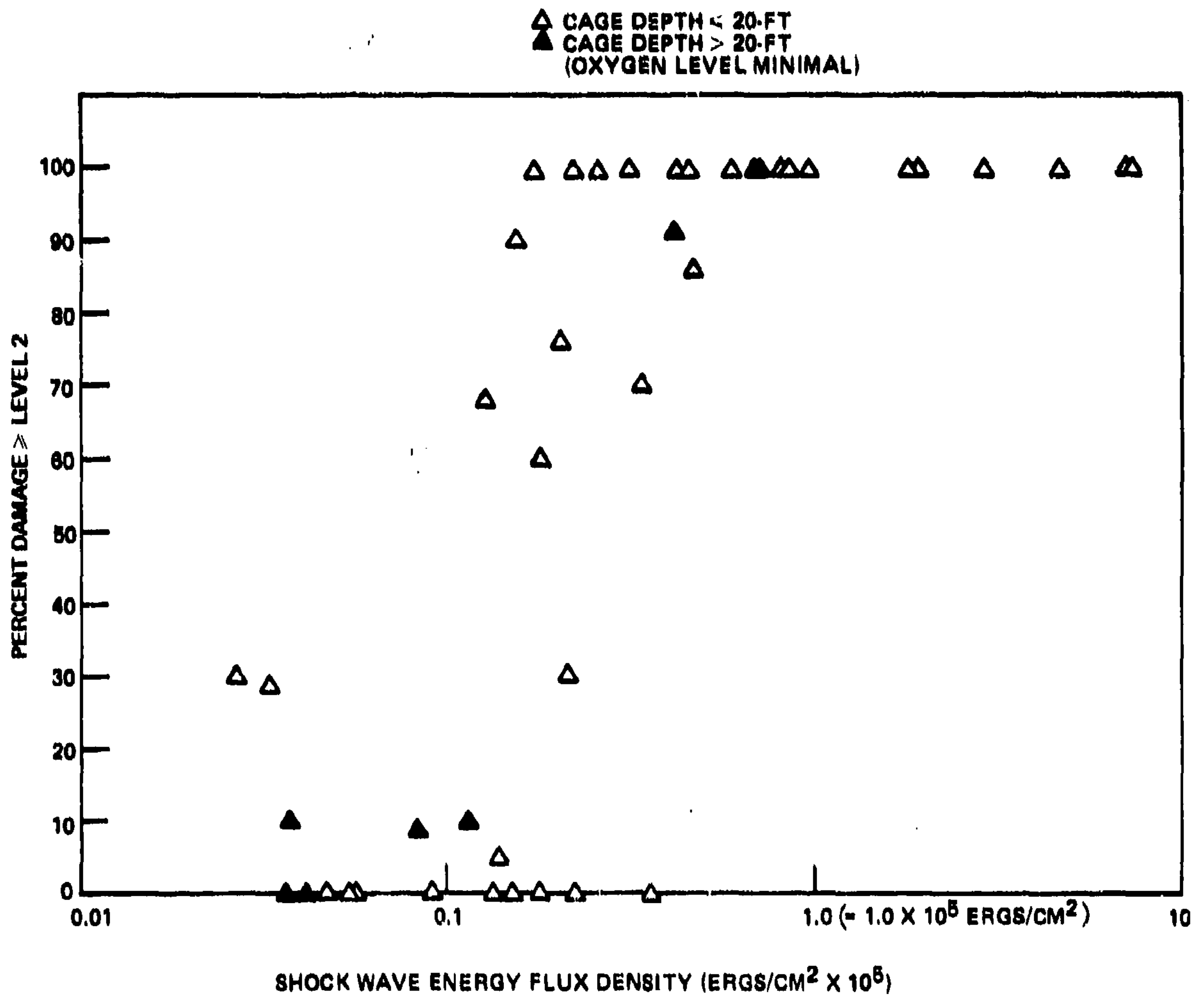

FIG. 14 SPOT DAMAGE VS SHOCK WAVE ENERGY

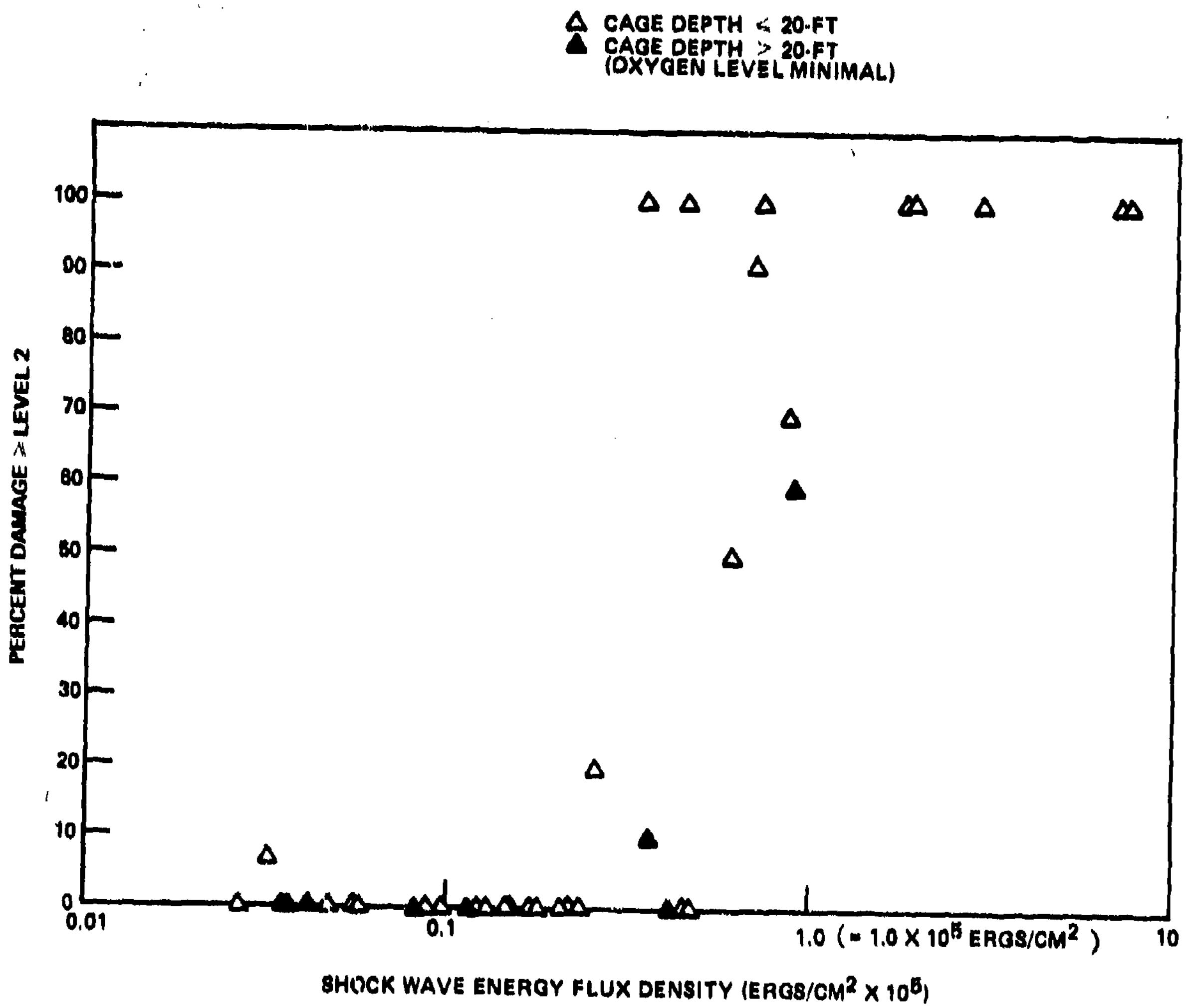

FIG. 15 WHITE PERCH DAMAGE VS SHOCK WAVE ENERGY

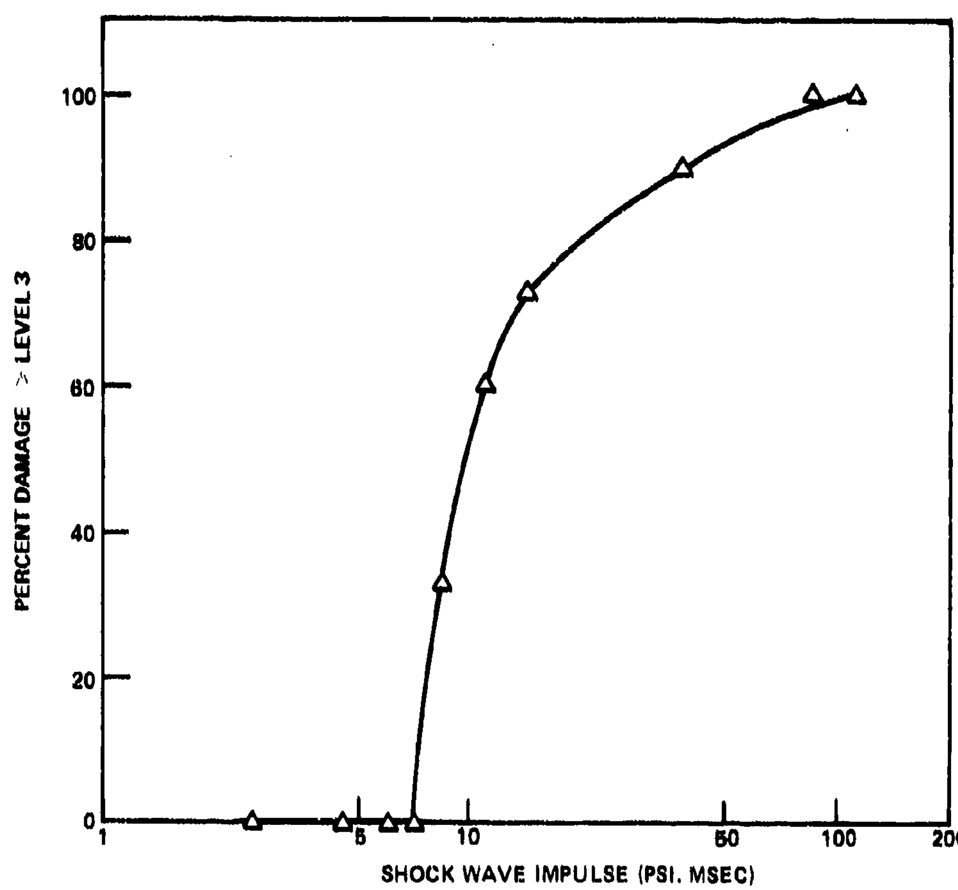

FIG. 16 SEVERE SPOT DAMAGE (> LEVEL 3) VS IMPULSE FOR FISH DEPTH = 10-FEET AND BURST DEPTH = 20-FEET.

relationship between the swimbladder's natural period of oscillation and the duration of the shock wave, may be of primary importance in the damage mechanism. To look for indications of this in the present data, we looked at the fish damage versus shock wave duration. The duration of the shock wave is taken as the time from the beginning of the shock rise to the ambient pressure crossing. Here we were looking specifically for swimbladder damage, and our damage criterion was changed from the damage level ≥ 2 used above. Since swimbladder damage occurs at damage levels of 3 and higher, our fish damage criterion for this section is the percentage of fish exhibiting damage of level 3 and higher. Figures 17 and 18 show this damage index plotted against shock wave duration for spot and white perch respectively. Since high peak pressures are associated with high damage levels, the data shown here are restricted to locations at which the peak pressure was less than 200 psi. There is nothing of particular interest in the spot data. The white perch data, however, appear to exhibit a strong resonance at a duration of 0.65 msec. All cases where significant level 3 damage was observed at low peak pressures occur at or near this shock wave duration. This may be a significant result, if it is supported by the outcome of the analytical study.

7.6 Probit Analysis

7.6.1 Probit analysis is the standard technique for evaluating biological tolerance data The theory and procedures of probit analysis are discussed by Finney (1952). Probit runs on several subsets of our data were made by the Lovelace Foundation for Medical Education and Research. The dose functions used for these runs were peak pressure, impulse, energy, and ΔP_1. Spot and white perch were included. Damage levels ≥ 1, ≥ 2 and ≥ 3 were used. A selection of ten combinations of these factors were run through the Lovelace probit computer program. Two of the resultant probit fits are shown in Figures 19 and 20. It is obvious from the appearance of these figures that the probit line is not a good description of the data. This is borne out by the chi squared test, which rejects these two fits, as well as all the other probit fits tried, at well beyond the 95% confidence level.

7.6.2 The implication of these probit runs is either that

(a) we have not found the correct dose function to correlate with fish damage, or

(b) the phenomenon under consideration does not conform to the sigmoid dose-response curve assumed in probit analysis.

Evidence for this latter possibility is found in the comparison of Figures 10 and 20. In Figure 10 we saw a clear indication of a relationship between ΔP_1 and spot damage. This same data set, when subjected to probit analysis, gives no indication of a correlation in Figure 20, and the probit fit is strongly rejected on a statistical basis. Although probit analysis has been proven generally useful in the evaluation of dose-response biological data, it should not be relied upon to the exclusion of other analysis techniques.

Finney, D. J., 1952, Probit Analysis, Cambridge University Press, Cambridge, England.

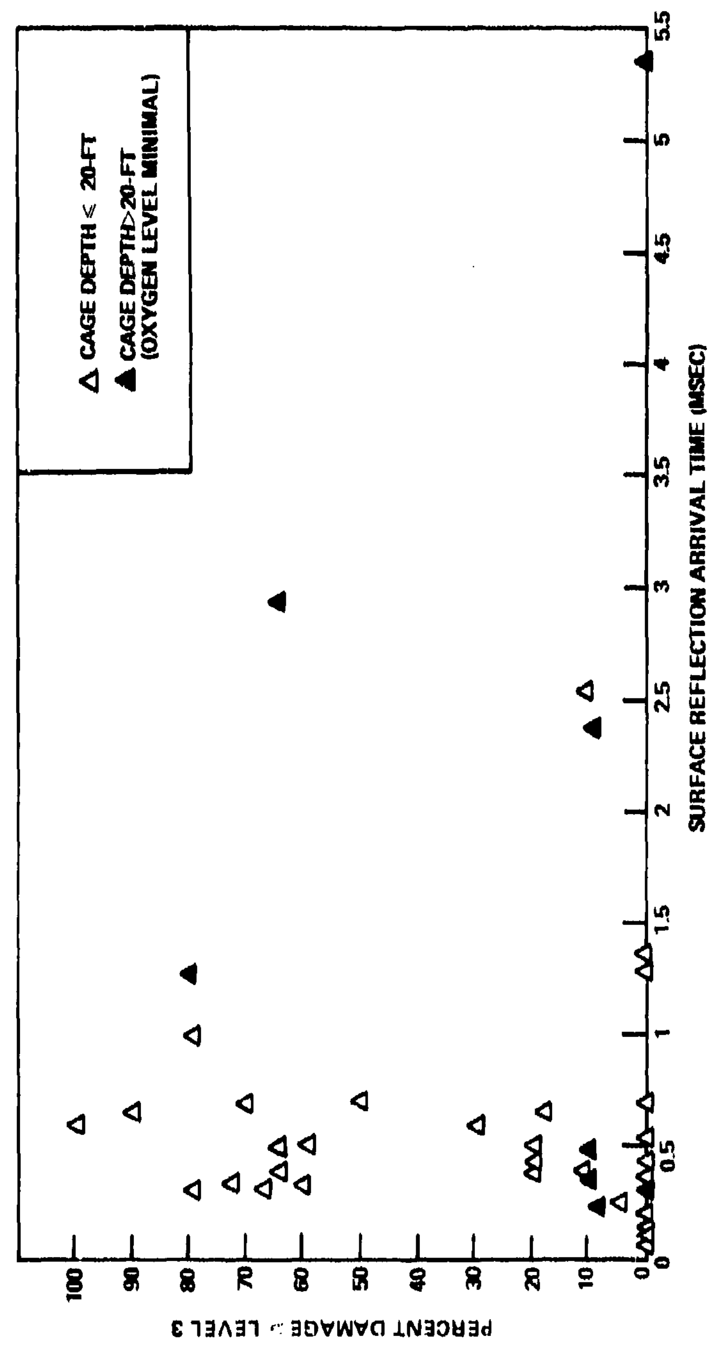

FIG. 17 SEVERE SPOT DAMAGE (≥ LEVEL 3) VS SURFACE REFLECTION ARRIVAL TIME (PEAK PRESSURE < 200 PSI)

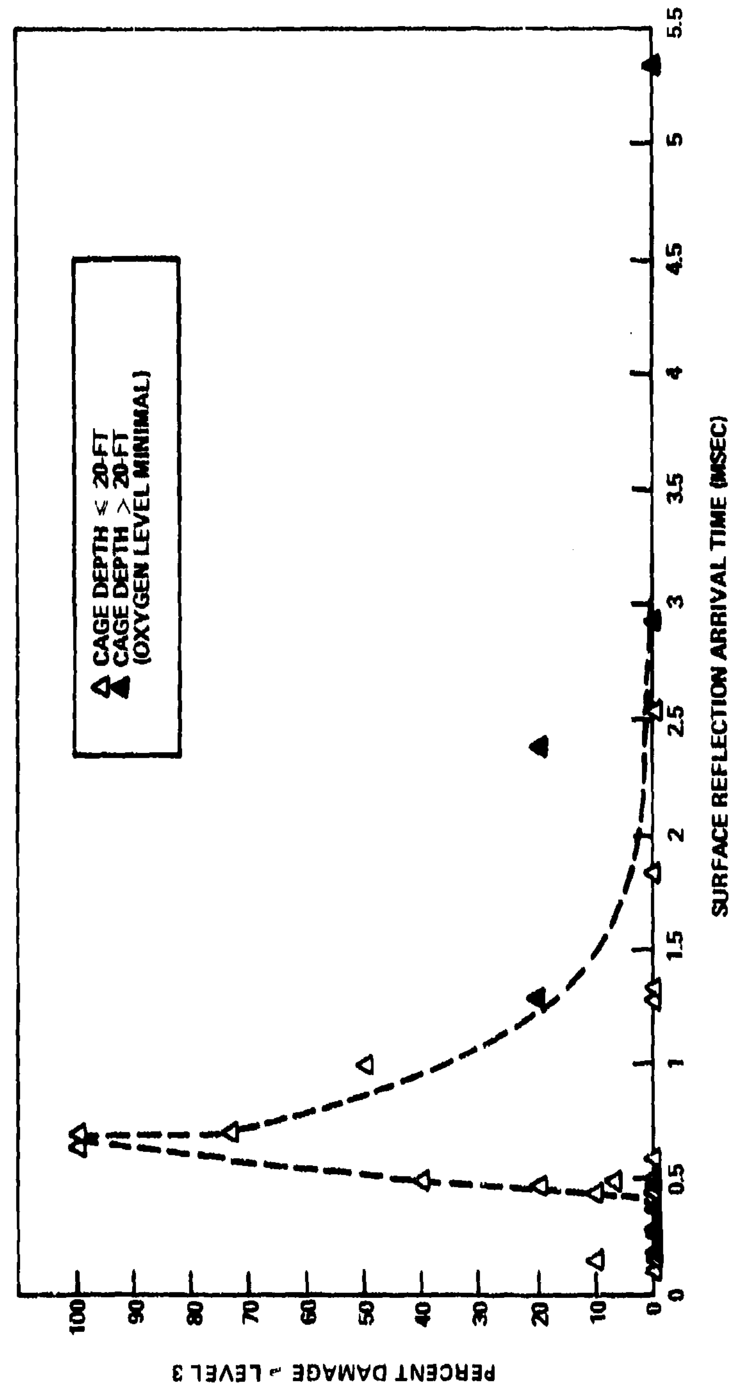

FIG. 18 SEVERE WHITE PERCH DAMAGE (≥ LEVEL 3) VS SURFACE REFLECTION ARRIVAL TIME

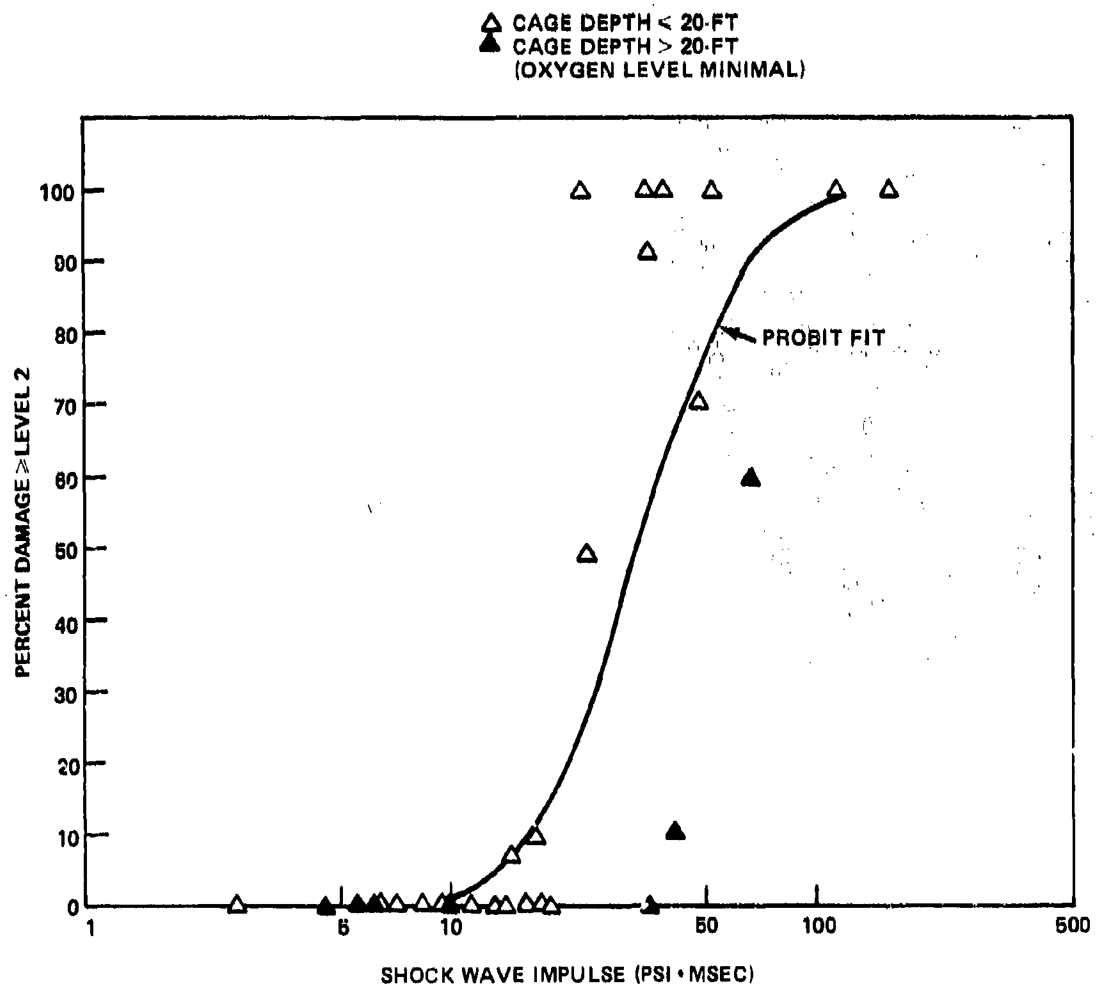

FIG. 19 PROBIT FIT: IMPULSE (WHITE PERCH)

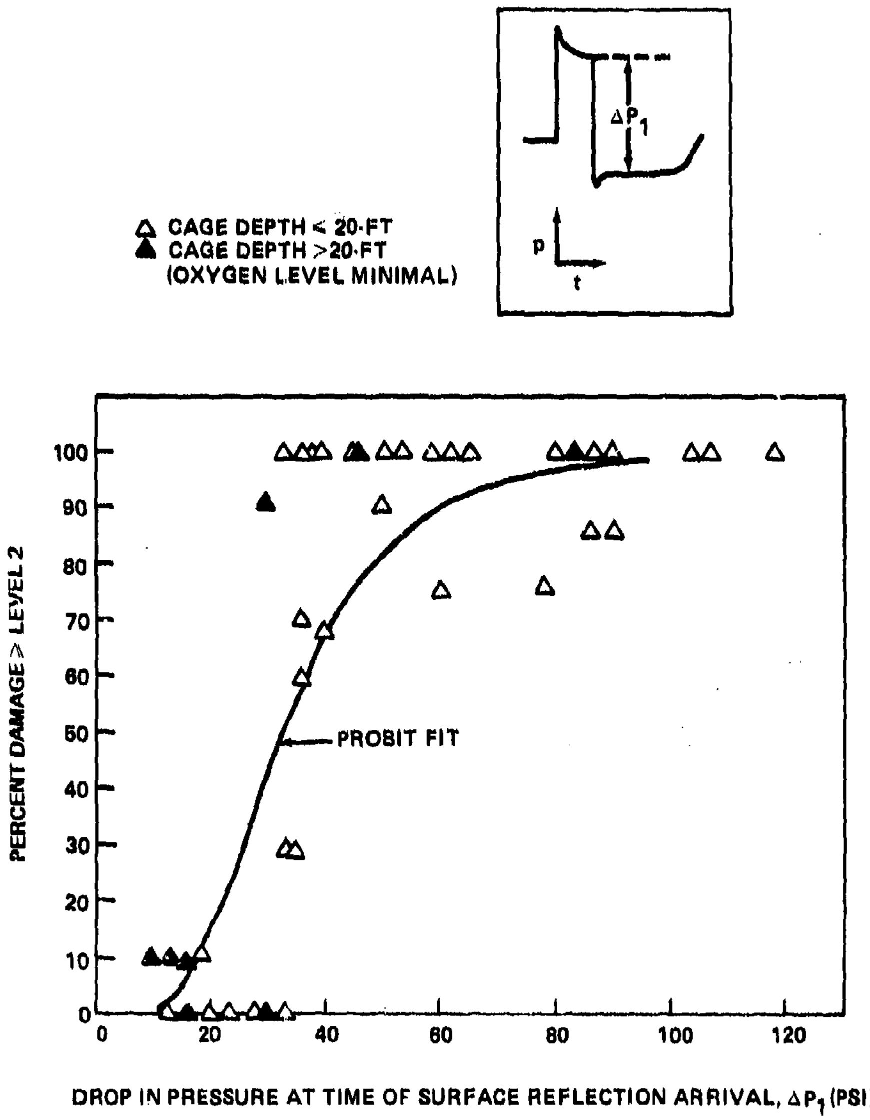

FIG. 20 PROBIT FIT: ΔP_1 (SPOT)

8. Conclusions

8.1 No correlation between the occurrence of bulk cavitation and fish damage is indicated in this data set.

8.2 None of the simple explosion shock wave parameters of peak pressure, impulse, or energy alone is a good criterion for the prediction of swimbladder fish damage.

8.3 The data for spot indicate a correlation of damage with the drop in pressure at the time of surface reflection of the shock wave. Below a value of ~35 psi only minimal damage occurs; above this value, significant damage occurs. There is no such correlation for the white perch, however.

8.4 At values of peak pressure less than ~200 psi, the white perch data show a strong resonance with the duration of the shock wave. All substantial damage occurs at or near 0.65 msec wave duration. There is no such correlation for the spot.

8.5 Data gathered elsewhere have indicated a correlation of severe damage to swimbladder fish with shockwave impulse, for cases where both the charge and the fish are at shallow depths. A subset of the present data confirms this. This correlation does not hold for deeper charge and/or fish depths.

8.6 Probit analyses of ten subsets of our data, covering different damage levels, explosion parameters and fish species, indicate that no acceptable probit fit for these data was found.

8.7 At this time, no general damage rule for swimbladder fish has been extracted from these data.

9. Acknowledgements

9.1 The author wishes to express gratitude to Dr. D. R. Richmond of the Lovelace Foundation For Medical Education and Research, for volunteering his time, energy, and expertise during the performance of the experiment, and for doing the probit analysis of the data. Dr. M. L. Wiley, J. S. Wilson and R. Miller of the Chesapeake Biological Laboratory did all collection, handling and damage evaluation of the fish specimens. The tests were done under the overall direction of Dr. G. A. Young. The members of the experimental team were R. L. Willey (barge foreman), P. A. Thomas, B. A. Robey, C. Goodwin Jr., W. R. Shaffer, R. B. Tussing, R. S. Price, T. Kibalo, W. W. McDonald and J. B. Gaspin, all of this Center. The author wishes to thank R. B. Tussing for his help in the preparation of the sections of this report concerning electronic instrumentation. The guidance of E. A. Christian during the planning, execution and analysis of this experiment is gratefully acknowledged.

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APPENDIX A

EXPERIMENTS WITH CRABS AND OYSTERS

A.1 As an adjunct to the deep water series described in the body of this report, two shots were fired in shallow water, to obtain data on damage to crabs and oysters in the vicinity of underwater explosions.

A.2 The shots were fired in 25-ft deep water in the Patuxent River, just north of Solomons Island. The rigging and instrumentation were similar to that used in deep water. The charges for both shots were Mk 82 general purpose bombs. These contain a nominal 200-lb charge. The two we used were loaded with tritinol (shot #532) and H-6 (shot #533).

A.3 The handling of specimens is discussed in Appendix B. Crabs were placed both in bottom cages, and cages 5-ft deep. Oysters were placed in bottom cages only. Rather than the detailed damage criteria used for fin fish, crabs and oysters were evaluated after each shot and classified as either a survivor, or a mortality.

A.4 Predictions of peak pressures and waveforms for large bottom explosions in shallow water cannot be made accurately. As a consequence, the gain on some channels of our recording system was set too high, and the records were clipped. For these records we did not obtain good pressure data. Observations on these two shots are summarized in Table A.1.

TABLE A.1 DATA SUMMARY

Shot #	W	DOB	H	D	P_{MAX}	I	E ($\times 10^5$)	Crabs S	Crabs K	Oysters S	Oysters K
532	200	25	50	25	1679	1720.	446.	10	0	7	2
		(on bottom)	110	5	484	48.8	1.29	-	-	15	5
			110	25	1264	677.	116.	12	0	10	0
533	200	25	40	25	>1600	--	--	5	7	11	1
		(on bottom)	75	5	1207	181.	12.2	-	-	9	1
			75	25	>1670	--	--	11	2	7	3

W = charge weight (lbs)
DOB = depth of burst (ft)
H = horizontal range (ft)
D = cage depth (ft)
> : record clipped at this value

P_{MAX} = peak pressure (psi)
I = impulse (psi-msec)
E = energy flux density (ergs/cm^2)
S = survived, K = killed
I and E wave integrated to the time of surface cutoff

A.5 Very little can be concluded from this set of data, except that crabs and oysters are highly resistant to damage from underwater explosions.

APPENDIX B

FINAL REPORT

ENVIRONMENTAL EFFECTS OF EXPLOSIVE TESTING

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B.1 Introduction

B.1.1 This report contains the data obtained by determining the extent of damage sustained by fishes and some invertebrates which were held in proximity to underwater explosions. The experiments were planned and conducted by personnel of the Naval Ordnance Laboratory, White Oak, Silver Spring, Maryland (now Naval Surface Weapons Center). Personnel of the Chesapeake Biological Laboratory collected the test animals and determined the degree of damage that they suffered in the explosions. The objectives of concern to this report are: A. To validate the shock wave underpressure prediction model for the mortality of fish with swimbladders in deep water. B. To investigate the effects of shallow-water mine tests on marine life in the Chesapeake Bay. A complete discussion of the theory concerning the effects of underwater explosions on fish is given by Christian (1973).

B.2 Materials and Methods

B.2.1 Test animals (fish and crabs) were collected in the Patuxent River in the vicinity of Solomons. A 25-ft semiballoon otter trawl with a 1/2-inch stretch mesh liner was used. The animals were dumped into a large tub of water directly from the trawl. The animals to be kept were then quickly sorted out by hand and fishes placed into a 275-gal holding tank which was supplied by flowing river water. Crabs (*Callinectes sapidus* Rathbon) were sorted into three size classes (small, medium, and large) to minimize cannibalism, and held in cages suspended from the NOL pier until they were used. Oysters (*Crassostrea virginica* (Gmelin)) were collected with a 48-inch oyster dredge and held in cages until used.

B.2.2 The holding tank full of fish was transferred from the collecting vessel to the test barge and immediately supplied with running water from a source about ten feet below the surface of the river (to obtain cooler, subsurface water). In addition, compressed air was blown into the tank through large wooden diffusers to provide additional aeration. Two holding tanks were maintained on the barge and they were alternately emptied and filled with fish. Fishes were held at least one day before being used in experiments to insure that they would have had time to begin to adapt to captivity.* Mortality due to capture and handling stress usually occurred in the first few hours after capture and was negligible in the experimental cages.

B.2.3 The experimental cages were cylinders 20 inches long and 12 inches in diameter. They were constructed of plastic mesh fabric, reinforced at the ends with steel wire rings. A door was created in each by tying one end in place with 3-4 pieces of light line (marline) which was cut off and replaced each time a cage was opened and reclosed. Some cages were made of mesh with 3/4-inch openings and others were of 1/4-inch mesh. Three cages were attached to a steel frame, which also supported the pressure sensors, at each of five stations.

B.2.4 Three species of fish were used in the tests: white perch (*Morone americana* (Gmelin)); spot (*Leiostomus xanthurus* (Lacepede)); and hogchoker (*Trinectes maculatus* (Bloch and Schneider)). These species were used because they were abundant, readily caught, and survived the stress of capture and handling fairly well. White perch and spot are swimbladder species, and the hogchoker has no swimbladder.

B.2.5 The following procedure was used to load the cages in preparation for an experiment. Three cages, attached to a steel supporting frame, were placed on end in one of two wooden troughs in which flowing water maintained a depth of about 12 inches. The fishes were caught from the holding tanks with small dipnets and quickly transferred in buckets of water to the cages. Each cage usually received at least ten fish (except in the first two tests in which we lost many white perch in the holding tanks), one species per cage, and the doors of the cages were then tied shut. If we intended to hold over some fish to detect delayed mortality, additional fish were used for that purpose. It became apparent after the third shot that hogchokers were not being injured so that thereafter we often used only 5 at some stations. When the rigging was ready to receive a set of cages, they were lifted overboard, submerging the fishes, and the frame fastened to the rigging with swivel eye snaps. Each cage received an identifying label, which was retained with the fish as they were processed after an explosion.

B.2.6 After an explosion, the cages were removed from the rigging and replaced in a trough. Then all the fish from a single station were dumped into a plastic bag and held in a container of iced water until all five stations had been retrieved. Chilling numbed or killed the fish and thus facilitated dissection and examination for injury caused by the explosion.

B.3 Assessment of damage to test animals

B.3.1 The numerical criteria of Hubbs, Schultz, and Wisner (1960) were used to classify the damage done to the caged fishes by the explosions.

(0) No damage.

(1) Only light hemorrhaging, principally in the tissues covering the kidney.

(2) Gasbladder intact, but with light hemorrhaging throughout the body cavity, with some damage to the kidney.

*The exception to this was shot #519, for which the fish were caught only a few hours before they were used.

(3) No external indication of damage, but with the gasbladder usually burst. Hemorrhaging and organ disruption less extreme than in (4) and (5), but with gross damage to the kidney.

(4) Incomplete break-through of the body wall, but with bleeding about the anus. The gasbladder is almost invariably broken and the other organs damaged as noted under (5).

(5) Rupture of the body cavity. The break is usually a slit just to the side of the midventral line. Associated with this severe damage is a burst gasbladder and gross damage to other internal organs. The abdominal contents are often completely lost or homogenized.

B.3.2 Crabs and oysters were examined for obvious external damage and those still alive after an explosion were held in flowing water for 24 hours to detect any delayed mortality. Some fishes were also held for several days to determine if there would be delayed mortality to those that were apparently not injured or that had probably sustained only light injury (numerical criteria 1 or 2).

B.3.3 Each day, while rigging and equipment were prepared for a test explosion, measurements were made of water temperature, conductively (from which salinity was calculated), and dissolved oxygen concentration. The measurements were made with a Martek Mark I, Model A, water quality monitoring system. As a control, a cage with several fish of each species was also put down for approximately one hour and taken up just before the explosion.

B.4 Results and Discussion

B.4.1 From July 16, 1973, to August 3, 1973, a total of 11 experimental explosions were detonated in water of 150-ft depth in Chesapeake Bay. The explosives were one to 68 lb spherical pentolite charges. The original design of of the experimental series was planned to place caged fishes to a depth of 50 ft. The water quality measurements (see Table 1) showed no measurable oxygen below 20 ft and this was confirmed when caged fish were killed when held below that depth. This condition persisted throughout the testing period. In consequence, the design was altered so that most cages were at depths of 20-ft or less. On four shots, some specimens were placed deeper than 20 ft. On shot #524, control fish placed at 40 ft depth survived, and test specimens from that depth were alive when recovered. On shots #525, 529 and 530, controls placed at 40 ft depth were dead when they were recovered after one hour submergence. The test specimens were probably dead of asphyxiation before shot time.

B.4.2 Examination of the data shows no apparent correlation between occurrence of cavitation and mortality (see Table 2). Often there were as many fish injured in non-cavitated areas as in cavitated areas. Interpretation of the fish damage data awaits complete analysis of the explosion pressure records. However, there was considerable difference in the amount of damage sustained by the three species of fish at some stations. Hogchokers were most resistant to damage by explosive forces. An occasional fish was described as having some light hemorrhaging (criteria 1) but in light of the rarity of such observations and the fact that most, including those at stations closest to the explosions, suffered no detectable damage, it is likely that the hemorrhaging which was observed was due to other cause. White perch were somewhat more resistant to damage than spot. In a number of instances (for example, shot Nos. 519 and 521) most or all of the spot at a station were injured (criteria 2 and 3) while white perch had no detectable injuries.

B.4.3 Different susceptibilities to injury as described above are due to structural differences among the three species. Hogchokers have no gasbladder which can be ruptured by changes in pressure, and they are very strongly constructed. The skin is thick and tightly bound to the underlying musculature and the scales are strongly attached. The viscera are compact and well protected in a small abdominal cavity. They easily withstand treatment that quickly kills spot and white perch.

B.4.4 The gas bladder is a structure that is readily ruptured by explosive forces that are transmitted through water. How these forces cause the types of damage that are observed is not understood. It is apparent, however, that the reason white perch were less damaged than spot is because they are more strongly constructed. White perch have larger, thicker scales, heavier ribs and other skeletal structures, firmer muscles, and thicker walls in the gas bladder than spot. The overall impression is that white perch are more solidly and strongly constructed and are thus able to tolerate a greater range of potentially damaging forces. Falk and Lawrence (1973) in their review on the effects of explosions on fish state that fish with thin air bladders are more easily injured than fish with thick air bladders.

B.4.5 It may be instructive to speculate about the series of events which may occur when fish with gas bladders are subjected to an underwater explosion. In the simplest terms, an explosion generates a wave of high positive pressure, which rapidly decays, is followed (depending on the geometric relationship of explosive charge to water surface and the fish) by a negative pressure wave (and cavitation where negative pressure reaches 0), and returns to normal. The effect of the positive pressure wave would be to rapidly compress the viscera into the space normally occupied by the gas of the gas bladder. Given sufficient velocity, the viscera would travel upward to strike the dorsal surface of the coelomic cavity and in so doing, bruise or rupture both the kidney and the displaced viscera as well. The ventral wall of the gasbladder, if it is not elastic and tough enough, might also be broken at this time.

B.4.6 The quick arrival of a negative pressure wave may compound the effects of sudden compression. If the gas in the gasbladder begins now to expand in response to rapid decompression, but the viscera still are moving upward in response to the earlier compressive force, then it seems certain that the gasbladder will be ruptured and the internal organs damaged by impact with the upper surface of the body cavity. Concurrently, expanding gas from the gasbladder would further damage delicate tissues and organs. It may also be that bubbles, formed in the blood when cavitation occurs, can expand enough to rupture capillaries.

Falk, M. R., and M. J. Lawrence. 1973. Seismic exploration: Its nature and effect on fish. Environment Canada, Fisheries and Marine Service. Tech. Rept. Ser. No. CEN T-73-9, V, 51 p.

B.5 Recovery of Injured Fish

B.5.1 We observed that fish which had had their gasbladders broken (criteria 3) often swam and maintained equilibrium in the cages after a shot. Indeed, very many fish with this degree of damage could not be distinguished by their actions from fish that had not been injured. Fish from selected stations at which damage was expected were held for 24 hours and longer (up to ten days) to observe if delayed mortality would occur (see Table 3). Many survived and showed signs of healing by the presence of adhesions among the viscera of several and development of new membranes across broken gasbladders in some others.

B.5.2 Although fish have sometimes displayed remarkable recuperative powers, it is the usual case that any injury or change of behavior from normal subjects those individuals to greatly increased chances of being eaten by predators. For example, experimental work by Coutant (1971) showed that juvenile rainbow trout and chinook salmon that had been subjected to thermal shock were selectively preyed upon by larger fish. It is likely, then, that any fish receiving injury of criteria 2 or above would have its performance so affected that there would be little chance to survive predation. Thus, we consider that any injury resulting in damage to kidney, gasbladder, and other viscera (criteria 2, or higher) will ultimately be fatal to most individuals.

B.6 Effects of Mine Tests on Benthic Animals

B.6.1 Little can be concluded from the mine tests in which spot, crabs, and oysters were used as the test animals. Some oysters and crabs were killed at stations nearest the explosions but many survived. The spot were killed or injured at all but the farthest stations.

B.7 Acknowledgment

B.7.1 We give thanks to Dr. Don Richmond, of the Lovelace Foundation, who volunteered his time to assist in the fieldwork and in other ways contributed much to the completion of the project; to Mr. Ricky Miller, who ably assisted in all phases of organizing and executing the fieldwork; to Capt. Wm. C. Keefe and Mr. C. K. Keefe of the R/V ORION for their expertise and cooperation in collecting the test animals; to the entire Naval Ordnance Laboratory crew who carried out the engineering and technical aspects of the larger project.

Coutant, C. C. 1971. Thermal pollution - Biological effects, pp. 1292-1334. In 1970 Literature review, water pollution. J. Water Pollution Control Federation.

Table 1. Water quality parameters as measured by a Martek Mark I, Model A, water quality monitoring system. Dissolved oxygen probe may have begun to malfunction on 19 July and ceased to function entirely on 2 August.

Shot number	Date and Time of day	Depth (ft)	Tempera-ture-°C	Specific conductivity (millimhos/cm)	Salinity (ppt)	Dissolved oxygen (ppm)
517	16 July '73	2	26	16.6	9.5	5.3
		5	26	16.6	9.5	5.4
	1205 hrs.	10	26	-	9.8+	5.1
		15	25.5	17.1	9.9	3.8
		20	25	18.8	11.1	1.2
		25	24	21.9	13.5	0
517	16 July '73	2	26.8	16.8	9.3	5.5
		5	26.8	16.7	9.4	5.7
	1415 hrs.	10	26.0	16.6	9.5	5.4
		15	25.8	16.9	9.8	4.3
		20	25.1	19.1	11.3	2.1
		23	24.5	20.4	12.3	0.4
		25	24.5	21.6	13.1	0.0
518	17 July '73	2	25.7	16.8	9.7	5.9
		5	25.7	16.8	9.7	5.6
	1140-1147 hrs.	10	25.6	16.8	9.7	5.0
		15	25.5	16.8	9.8	3.2
		20	25.5	17.2	10.0	2.5
		25	24.3	23	14.1	0
		30	23.5	26	16.4	0
		35	23.0	27.4	17.6	
519	18 July '73	2	28.2	15.9	8.7	5.2
		5	27.9	15.5	8.5	5.4
	1130 hrs.	10	26.0	16.0	9.2	5.3
		15	25.8	16.2	9.3	5.0
		18	25.5	16.5	9.6	4.8
		20	25.0	18.9	11.2	2.2
		22	25.0	19.9	11.9	0.8
		24	24.8	21	12.6	0.2
		25	24.3	22.6	13.8	0
		30	24.0	27.2	17.0	0
521	19 July '73	5	26.2	15.8	9.0	2.4 ?
		10	26.0	15.8	9.0	3.8 ?
	1230 hrs.	15	25.9	15.5	9.1	3.9 ?
		17.5	25.7	16.4	9.5	1.2 ?

TABLE 1 (Cont'd)

Shot number	Date and Time of day	Depth (ft)	Tempera-ture-°C	Specific conductivity (millimhos/cm)	Salinity (ppt)	Dissolved oxygen (ppm)
521	20 July '73	2	26.2	17	9.7	0.6 ?
		5	26.0	17	9.8	2.2
	1100 hrs.	10	25.9	17.1	9.9	2.8
		15	25.9	17.3	10.0	2.9
		20	25.9	17.3	10.0	1.15
522	23 July '73	2	25.8	17.3	10.0	0
		5	25.8	17.3	10.0	1.0
	1130 hrs.	10	25.8	17.3	10.0	1.2
		15	25.8	17.5	10.1	0.3
		18	25.7	18.2	10.6	0.0
523	24 July '73	2	27.0	17	9.6	3.6
		5	27.0	17.2	9.7	3.5
	1130 hrs.	10	26.7	17.3	9.8	3.0
		15	26.1	17.4	10.0	2.3
		18	26.0	17.4	10.0	1.1
524	27 July '73	2	26.3	17.9	10.3	0.84
		4	26.3	17.9	10.3	0.95
	1030 hrs.	10	26.5	17.8	10.2	0.9
		15	26.4	17.8	10.2	1.2
		21	26.3	17.8	10.2	1.0
		26	26.5	17.9	10.2	
525	30 July '73					
		2	25.8	18.2	10.6	4.8
		5	26.0	18.2	10.5	4.8
		10	25.8	18.3	10.6	3.9
		15	25.5	18.4	10.8	2.8
		20	25.3	19.0	11.2	2.7
		23	25.0	20.6	13.3	2.0
		25	24.2	22.4	13.7	0
529-530	2 Aug.'73	2	27	18.8	10.6	
		5	27	18.8	10.6	
		10	27	18.8	10.6	
		15	26.9	18.8	10.6	
		20	26.9	18.8	10.6	
		30	26.8	18.8	10.6	
531	3 Aug.'73	2	27	18.8	10.6	
		5	27	18.8	10.6	
		10	27	18.6	10.4	
		15	27	18.6	10.4	

TABLE 2. Summary of data from experimental explosions showing numerical classification of damage for spot and white perch. Abbreviations: DOB = depth of explosive charge; H = horizontal distance from explosion, ft; D = depth of cages below water surface, ft; P_{MAX} = measured maximum pressure level, psi; S and M (under oyster and crab columns) = survival and mortality, respectively. All underpressures are minus values.

TABLE 2

Shot	Chg. Wt.	DOB	H	D	P_M	Under-pressure Surf.	Under-pressure Bot.	Cavitation Surf.	Cavitation Bot.	Numerical classification of damage: Spot 0	Spot 1	Spot 2	Spot 3	Spot 4	Spot 5	Spot %Killed	White Perch 0	Perch 1	Perch 2	Perch 3	Perch 4	Perch 5	Perch %Killed
517	1	5	42	5	311	17	7	Yes	No			1	9						1	3			
			42	20	321	15	7	No	No				10							3			
			118	5	*	+	+	No(?)	No(?)	10							4						
			118	20	104	19	7	No	No	10							3						
			190	5	64	5	7	No	No	13							5						
518	8	20	82	5	363	18	15	Yes	No				10										
			82	20	415	20	20	No	No				11										
			250	5	107	17	18	Yes	Yes			6	16										
			380	20	71	16	16	No	No			9	2										
			380	10	75	12	14	No	No	1		3	6										
519	8	40	82	5	*	19	17	Yes	Yes				9							10			
			82	20	267^{Δ}	22	23	No	Yes			1	9						1	9			
			250	5	86^{Δ}	15	17	Yes	Yes			4	7						6	4			
			380	20	55^{Δ}	19^{Δ}	20^{Δ}	No	No	10							10						
			380	10	69^{Δ}	18	17	Yes	No			7	3				10						
521	31	30	125	10	360	23(?)	20	Yes	Yes				8	3						2	8		
			370	5	121	17	17	Yes	Yes			4	16				10						
			370	18	116	24	24	Yes	Yes			3	7					1	2	8			
			580	10	*	*	*	*	*	6	3	4	7				10						
			678^{Δ}	10	64^{Δ}	11	18	No	Yes	19			1				10						
522	31	30	125	10	388	19	19	Yes	Yes				9	2						2	8		
			370	5	125	17	17	Yes	Yes		3	4	13	1			8	2					
			370	18	105^{Δ}	20	22	No	Yes			1	9							10			
			580	10	60^{Δ}	12	19	No	Yes	4	3	2	13				10						
			700	10	69(?)	13	18	No	Yes	10							10						
523	31	15	125	10	343	19	19	Yes	Yes				5	5			8			4	6		
			370	5	99	12	17	No	Yes		5	9	7				10						
			370	18	129	11	22	No	Yes			4	7				1	4	5				
			580	10	*	*	*	*	*	6		4					10						
			700	10	40(?)	7	18	No	Yes	7		3					10						

524	68	40	170	10	382	20	16@	Yes	No				8	2							10
			500	10	118	18	9.5	Yes	No	1 (Dead)	2	8	10				10				
			500	18	111	22	10	Yes	No	1	4	5	10				6	2	1	1	
			500	40	83Δ	21	17	No	No			2	8				2		6	2	
			780	10	61	18	15	No	No	1	1	3	5				9	1			
525	68	70	170	10	346	20	20	Yes	Yes					10							10
			500	10	104Δ	19Δ	19Δ	Yes	Yes				20				Not recorded (10 fish)				
			500	18	113	22	20	Yes	No			2	8					3	2	5	
			500	40	91Δ	19	25	No	No			9	1					4	4	2	
			780	10	62	19	19	Yes	Yes			8	1	1			3	1		1	
529	1	20	110	40	119Δ	14	18	No	No		1	3	7				5	6			
			190	5	68	19	8	Yes	No	18	3						19				
			190	30	62	13	6	No	No	6	4		1				9	1			
			262	5	37	7	5	No	No		11							10			
			262	30	43	10	5	No	No		10						6	4			
530	1	40	110	40	123	13	12	No	No	1	9						2	7	1		
			190	5	69	18	13	Yes	No	12	5		2				20	1			
			190	30	71	14	11	No	No	7	2		1				10				
			262	5	42	13	13	No	No	10							10				
			262	30	43	13	10	No	No	8	1		1				10				
531	8	40	250	10	111	18	18	Yes	Yes		3	2	5							10	
			315	10	75	18	18	Yes	Yes	6	9	2	4				10	4		1	
			380	10	68	15	15	No	No	2	2	5	1				9	1			
			540	10	46	14	16	No	No	5	2	1	2				10				
			760	10	29	6	11	No	No	10							10				
																Oysters		Crab			
																S	M	S	M		
532	200	25	50	25	1679	41(?)		Yes					1	3	1	10		7	2		
			110	5	484	18		Yes						7				15	5		
			110	25	1264	30(?)		Yes								12		10			
			650	5	39Δ	8		No		7	3										
			650	10	55Δ	15		No				4	6								
533	200	25	40	25	>1600	51(?)		Yes						10		6	7	11	1		
			75	5	1207	>36(?)		Yes						10				9	1		
			75	25	>1673	23		Yes								11	2	7	3		
			440	5	239	17		Yes		?	5	4									
			440	10	257Δ	18		Yes		1:	1	8									

* - No record; + No calibration; (?)-Means best guess; Δ-From Lo Gain Tape;
@ - Actual H from arrival time (700 nominal); >-Overloaded channel, signal at least this great.

TABLE 3. Summary of data showing length of time that fish were held over after an explosion and how many survived in each damage category. $D_0 = 10$ means that 10 fish in damage category 0 survived for the holding time, $D_1 = 4$ means that 4 fish survived damage of category 1, etc.

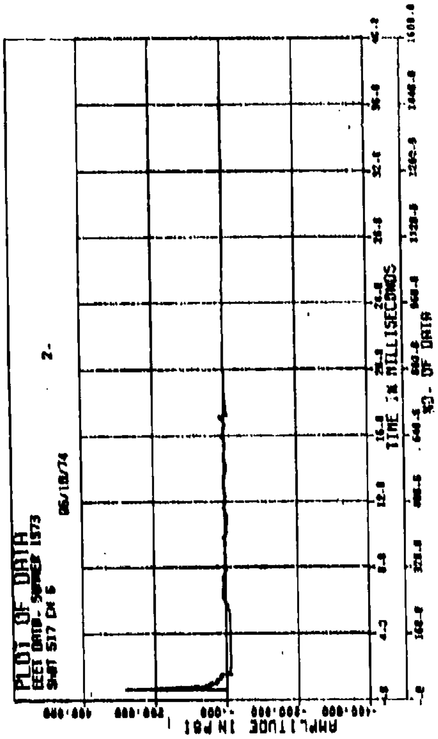
TABLE 3

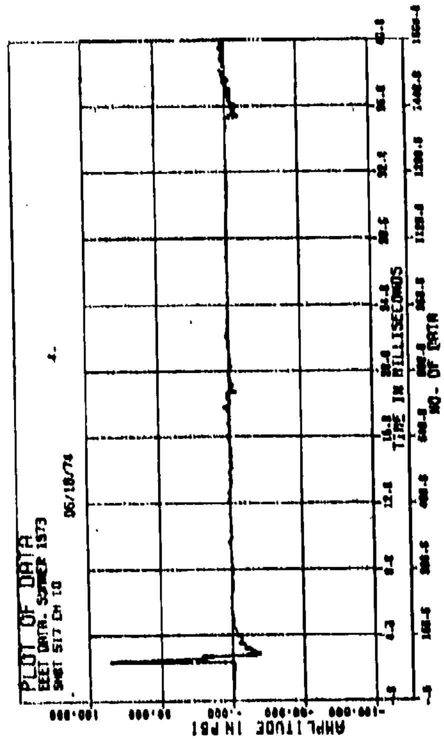
Shot no. and Station no.	Date of shot	Date examined	Approx. time elapsed (hrs)	Species and number held over	No. surviving in each damage category	Remarks
521 700-10	20 July	23 July	72	White perch 10 Spot 21 Hogchoker 5	D_0=10 D_0= 20, D_3=1 D_0=5	No mortality or damage attributed to explosion.
523 700-10	24 July	26 July	48	White perch 10 Spot 10 Hogchoker 10	D_0=10 D_0=7, D_2=3 D_0=10	Two white perch died from bacterial finrot.
524 500-20	27 July	30 July	68.5	White perch 7 Spot 18 Hogchoker 5	D_0=5,D_1=1,D_2=1 D_0=1,D_1=4,D_2=5,D_3=8 D_0=5	Three white perch and 2 spot were immediately killed by the explosion.
524 500-10	27 July	30 July	68.5	White perch 10 Spot 14 Hogchoker 5	D_0=10 D_1=1,D_2=7,D_3=6 D_0=5	Five spot were killed initially, 1 (D_3) lived 2.5 hrs., and 1 (D_1) lived $<$24 hr.
525 500-10	30 July	31 July	20	White perch 10 Spot 20 Hogchoker 5	D_0=10 D_3=12 D_0=5	Four spot were killed initially, 4 more (D_3) died overnight.
525 500-20	30 July	31 July	20	White perch 7 Spot 10	D_1=3,D_2=1,D_3=3 D_2=2,D_3=7	Three white perch were killed initially. One spot (D_3) died overnight.
529 190-5	2 Aug	3 Aug	24	White perch 10 Spot 10	D_0=10 D_0=7, D_1=3	
530 190-5	2 Aug	3 Aug	24	White perch 10 Spot 10	D_0=10 D_0=5,D_1=3,D_3=2	
531 250-10	3 Aug	13 Aug	240	White perch 5 Spot 5	D_0=1,D_1=1,D_3=3 D_0=2,D_3=2	One white perch (D_3) dead on 9 Aug. One decomposed spot found on 13 Aug. Rest of fish were living but were killed when moved to different aquarium. Two spot and one white perch had no observable damage; others had adhesions and/or repaired break in gasbladder.

APPENDIX C

DIGITIZED PRESSURE-TIME HISTORIES

C.1 This Appendix contains plots of all digitized, Low gain pressure-time records. The plots are identified by Shot #, and Channel # ("Shot" and "Ch" respectively in the figure headings). Using Table 2 on page 15 of the main body of this report, each plot may be identified as to charge weight and experimental geometry.


PLOT OF DATA
EET DATA. SUMMER 1973
SHOT 517 CH 6
05/18/74
2.
TIME IN MILLISECONDS
NO. OF DATA
AMPLITUDE IN PSI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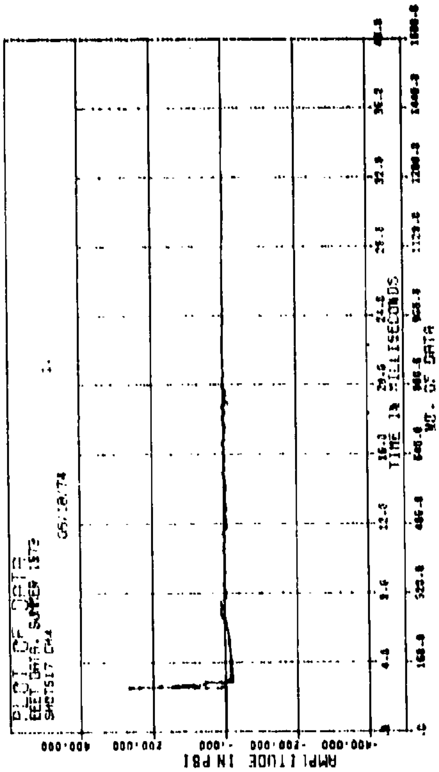
AMPLITUDE IN PSI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SHOT517 CH4
05/18/74
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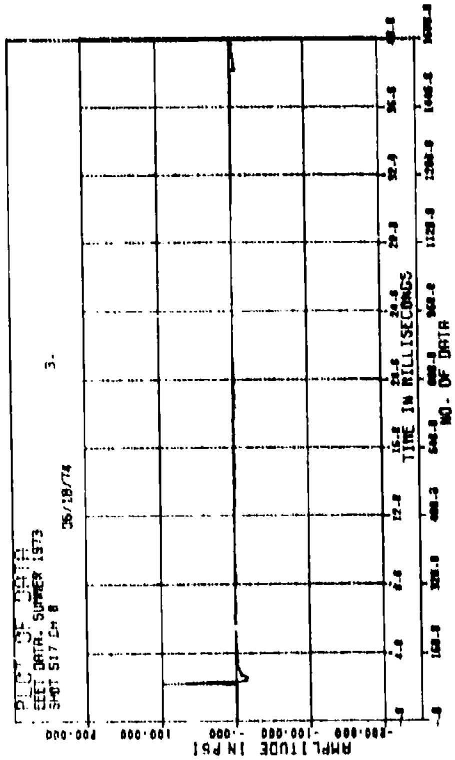
NO. OF DATA
AMPLITUDE IN PSI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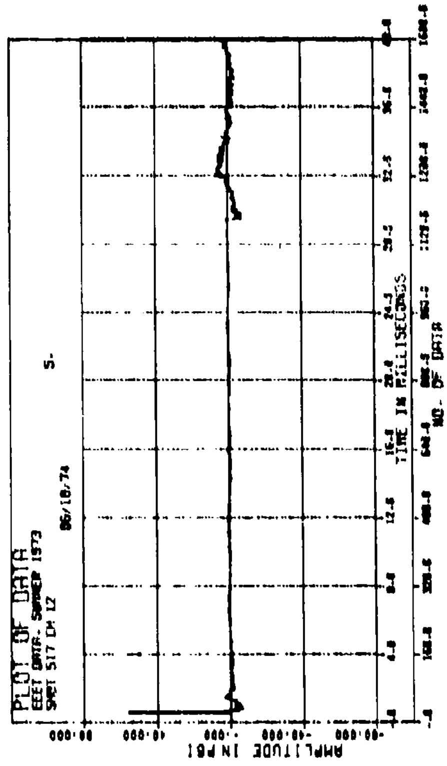
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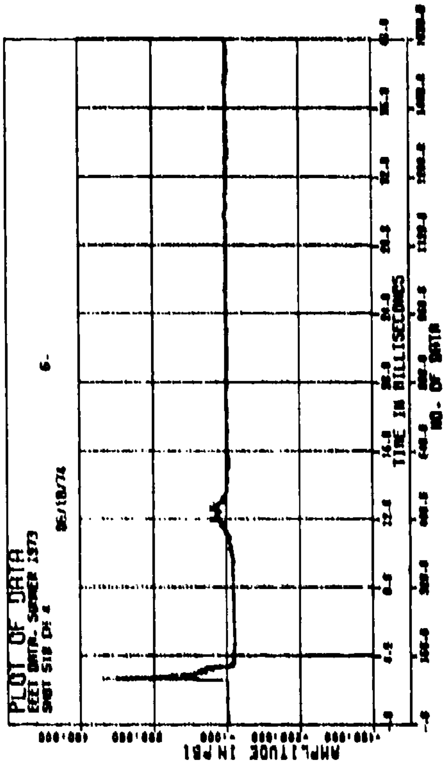
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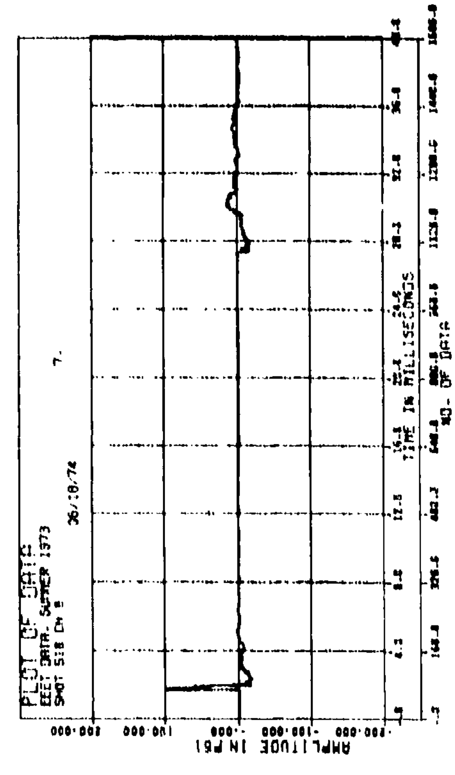
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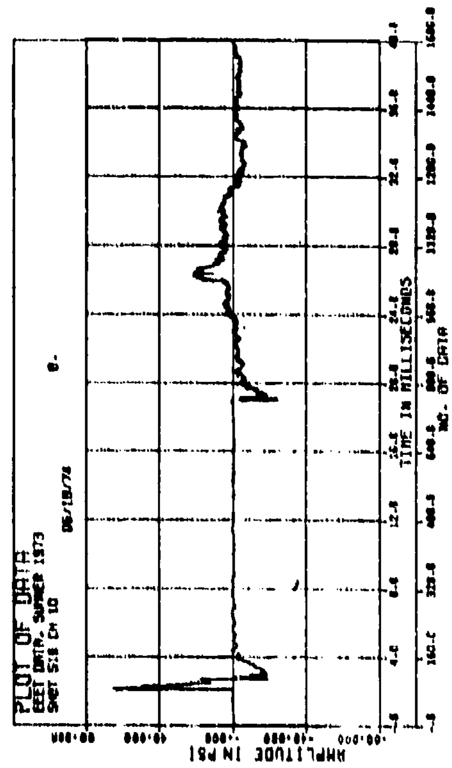
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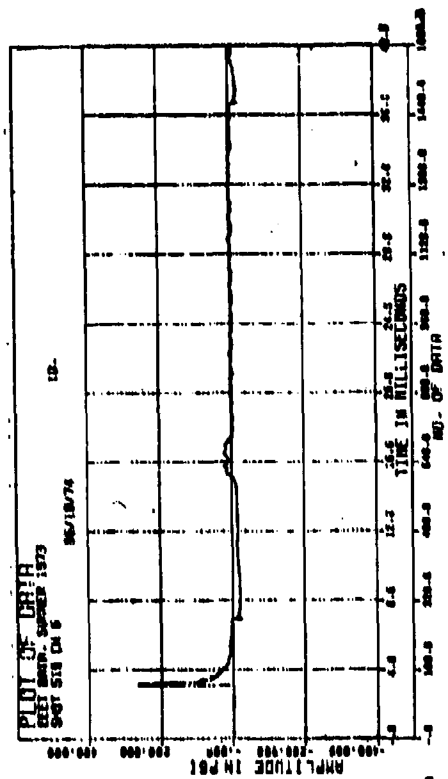
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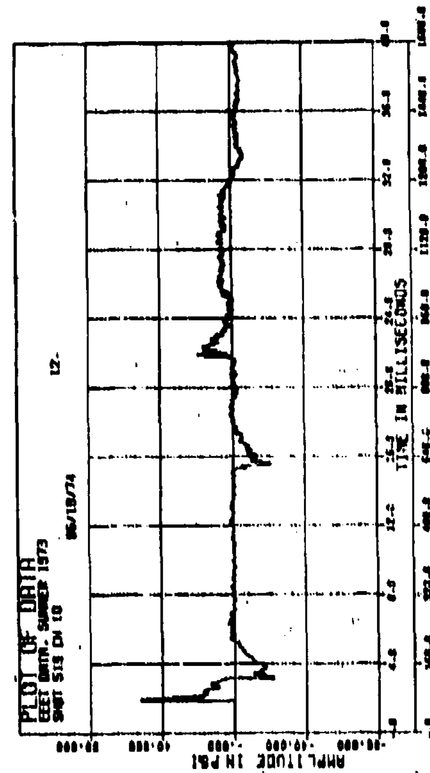
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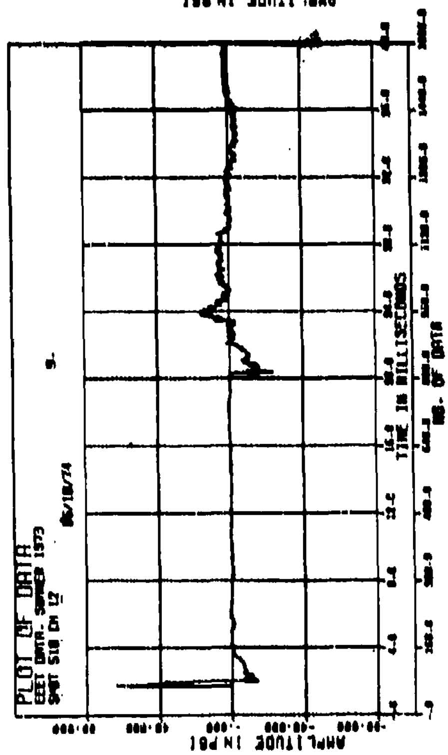
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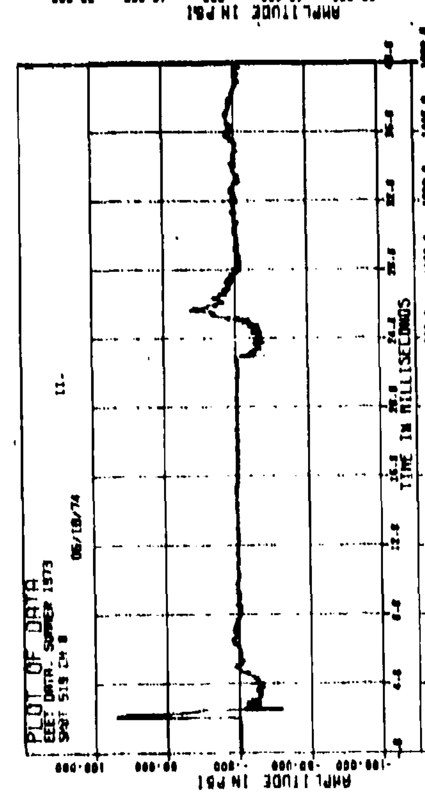
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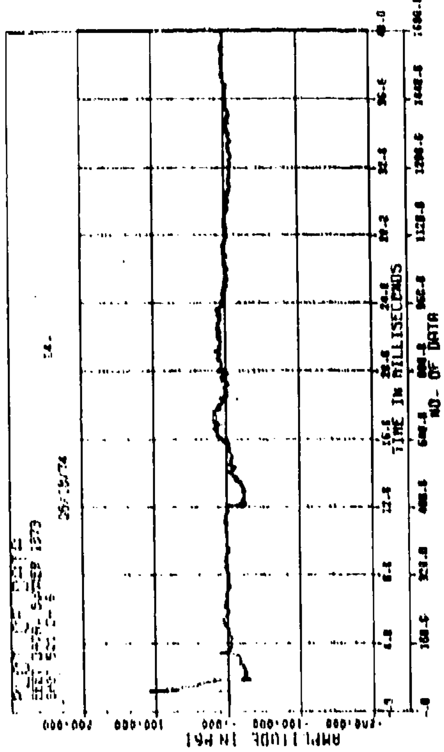

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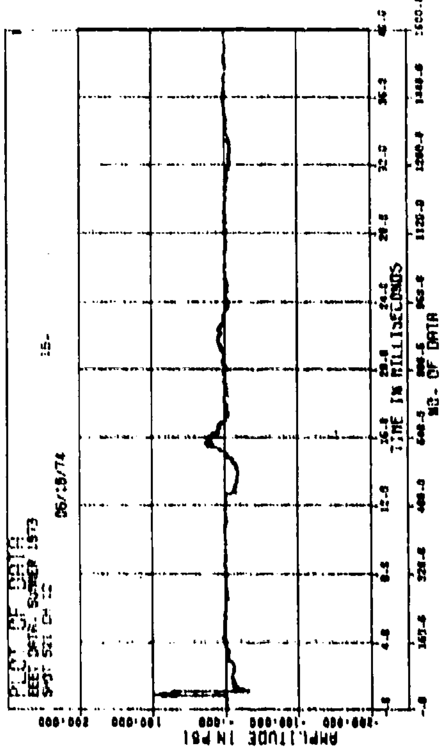

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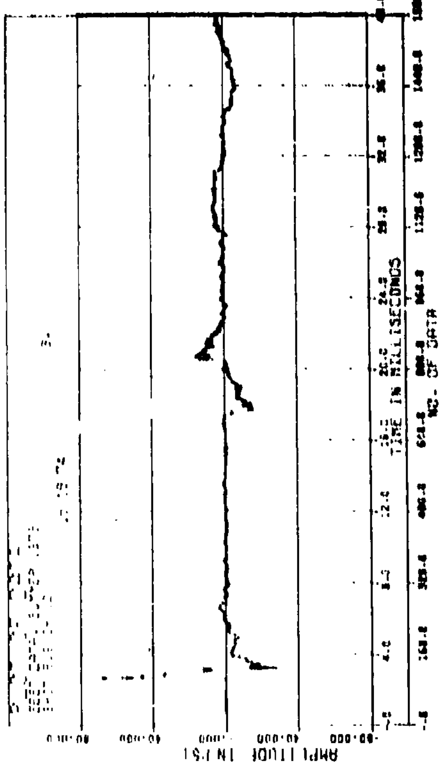

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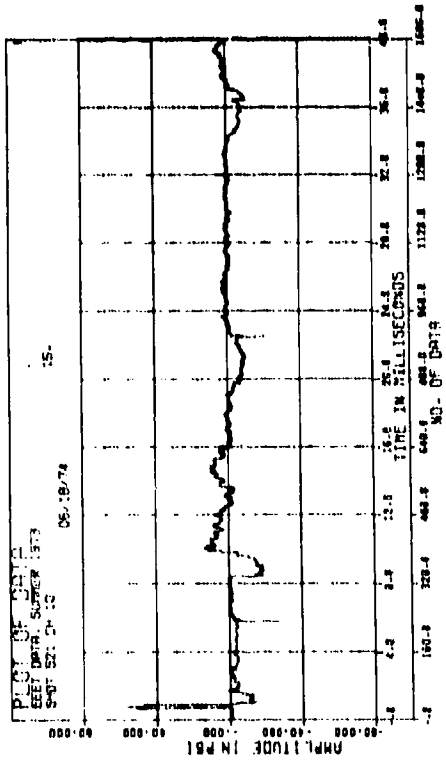

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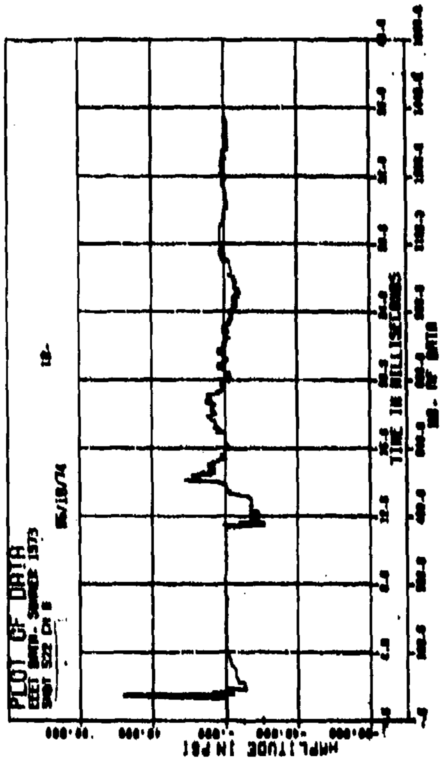
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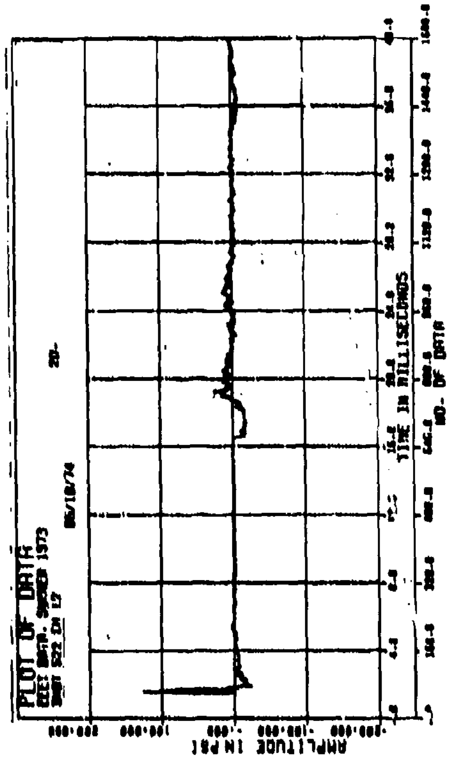
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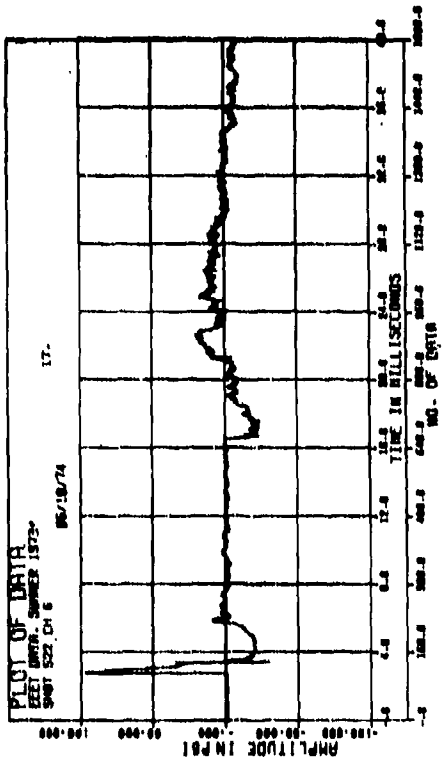
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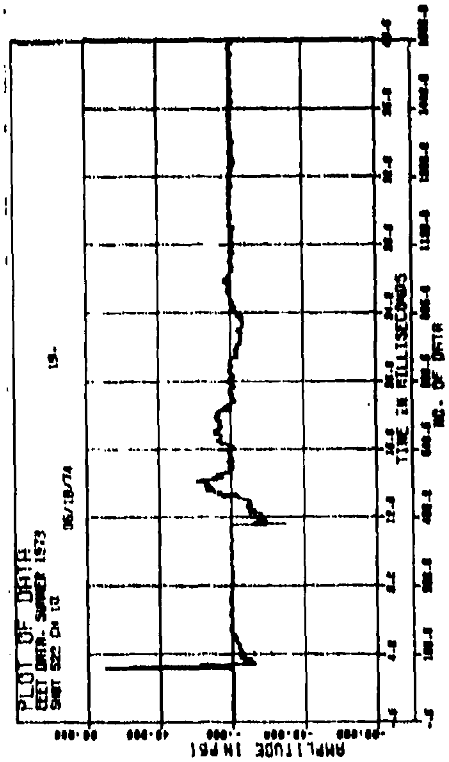
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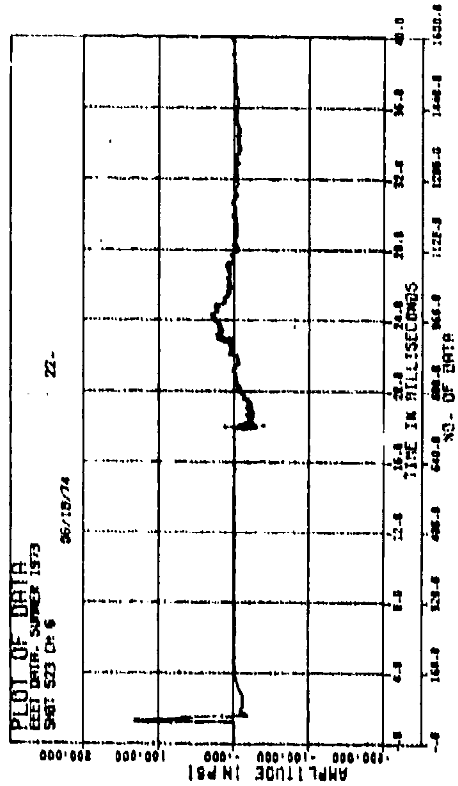
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SHOT 523 CH 6
06/15/74
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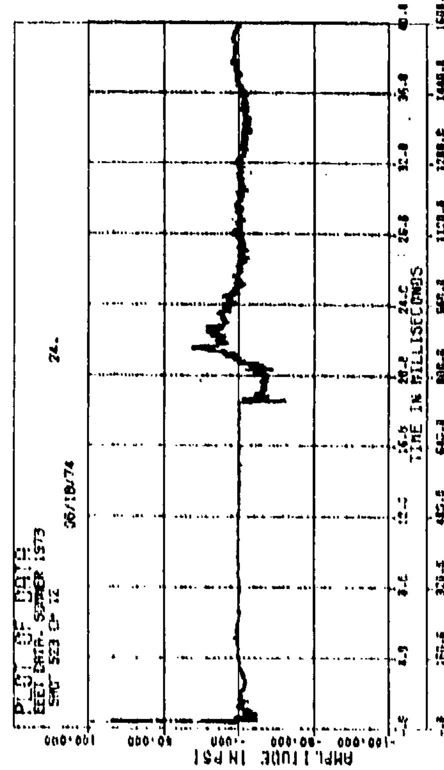
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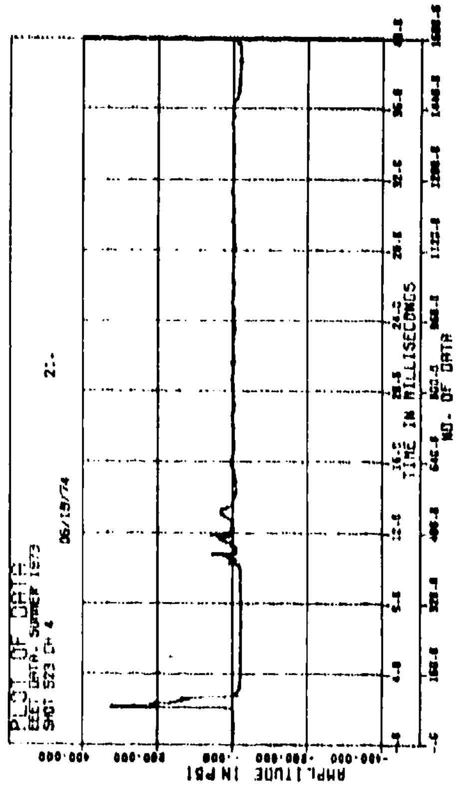
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06/15/74
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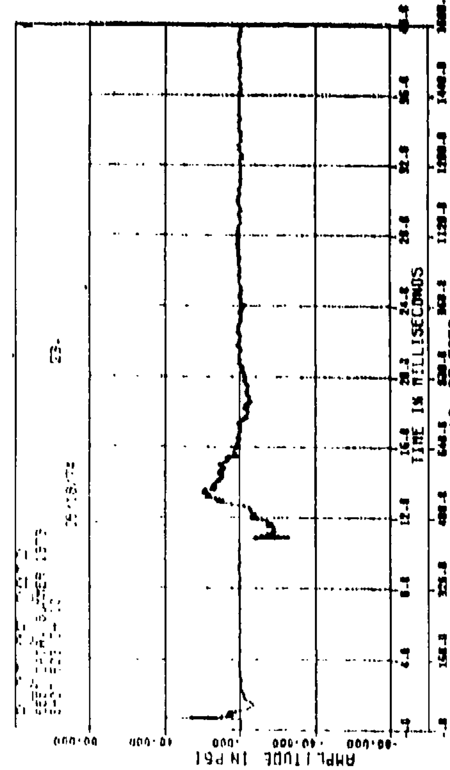
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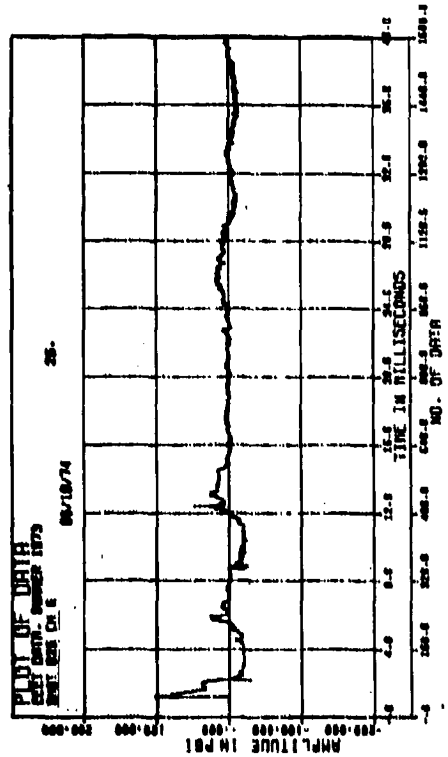
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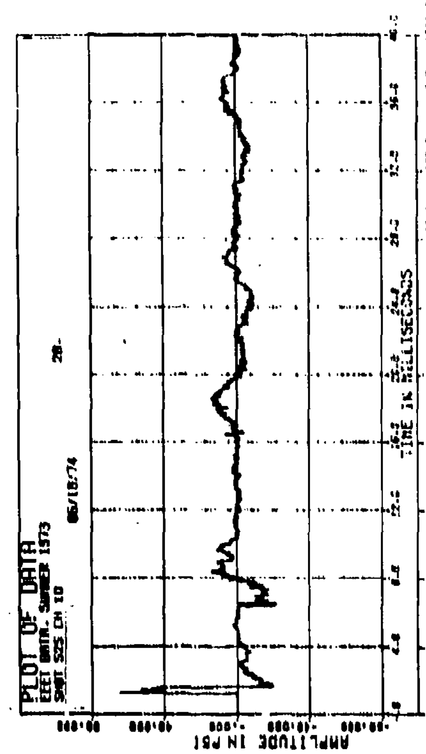
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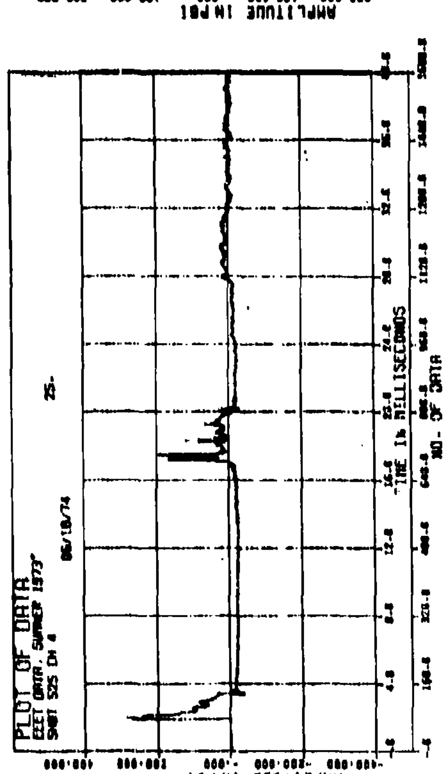
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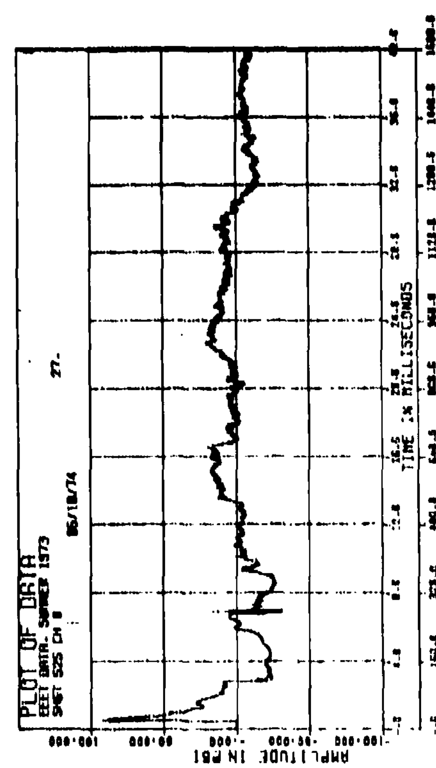
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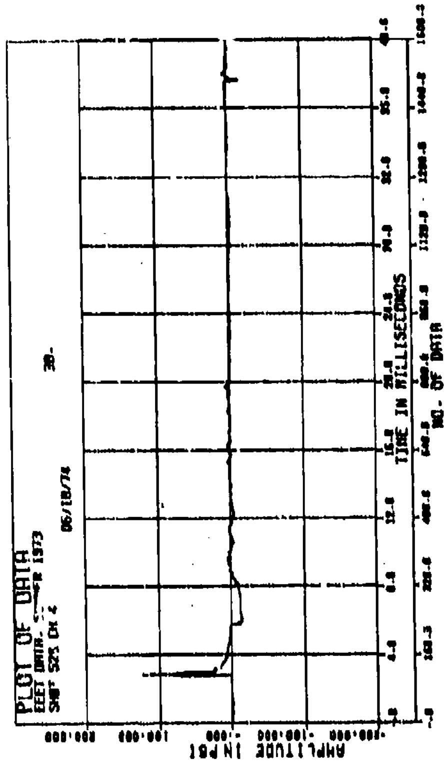
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06/18/74
30-
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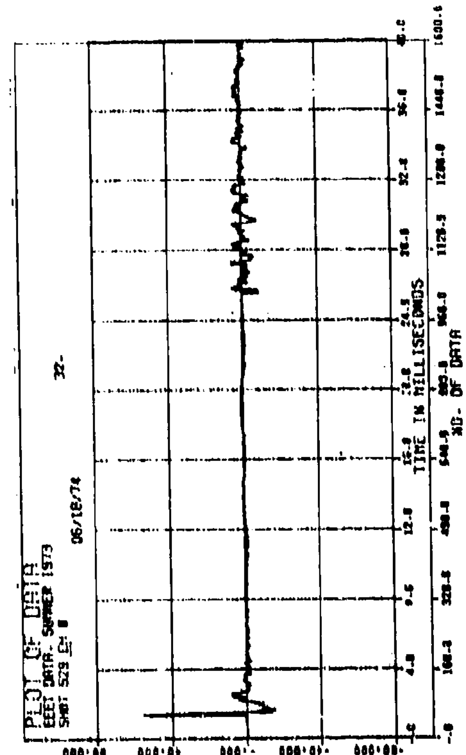
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06/18/74
32-
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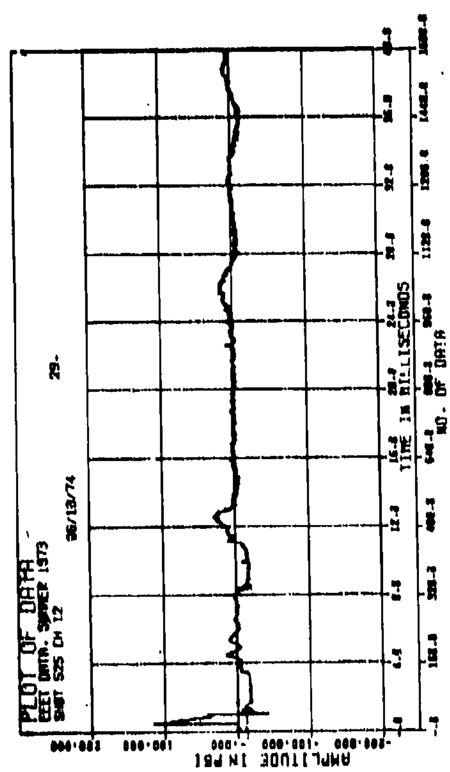
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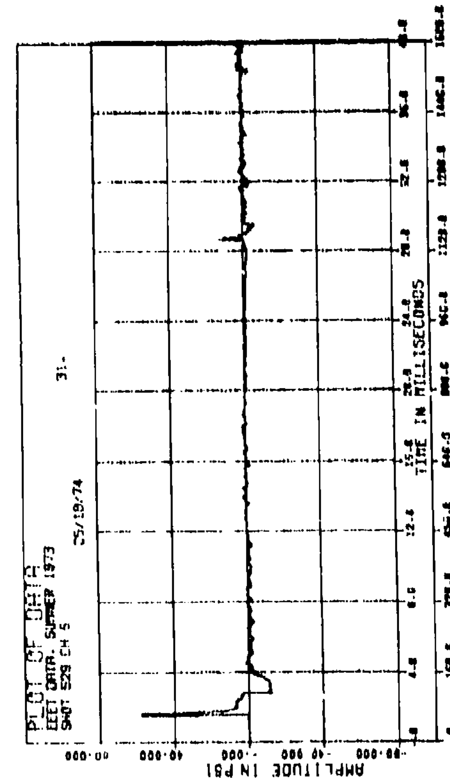
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SHOT 529 CH 5
31-
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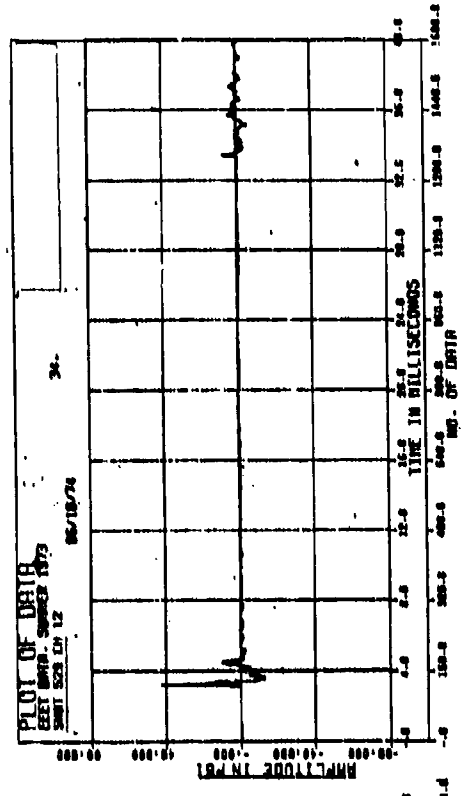
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TIME IN MILLISECONDS
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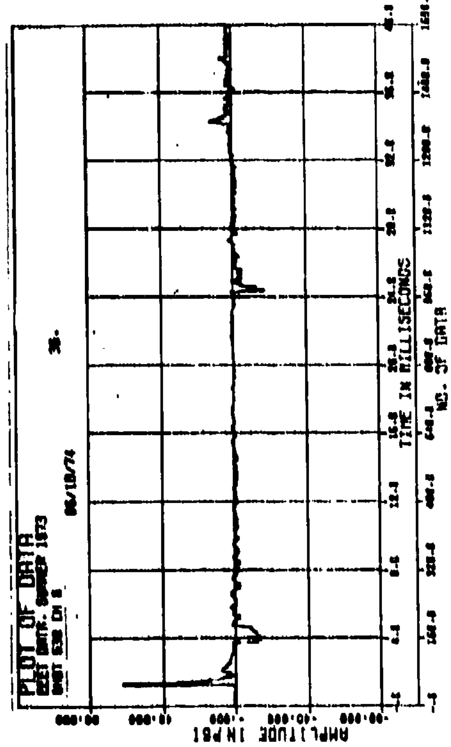
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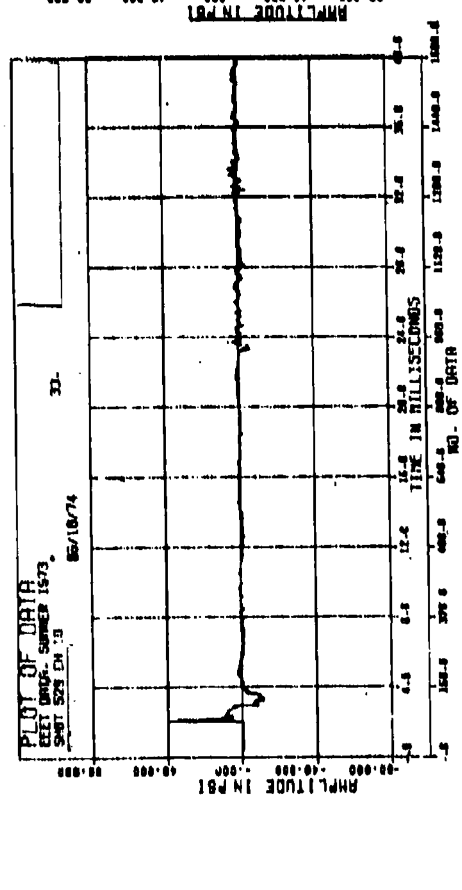
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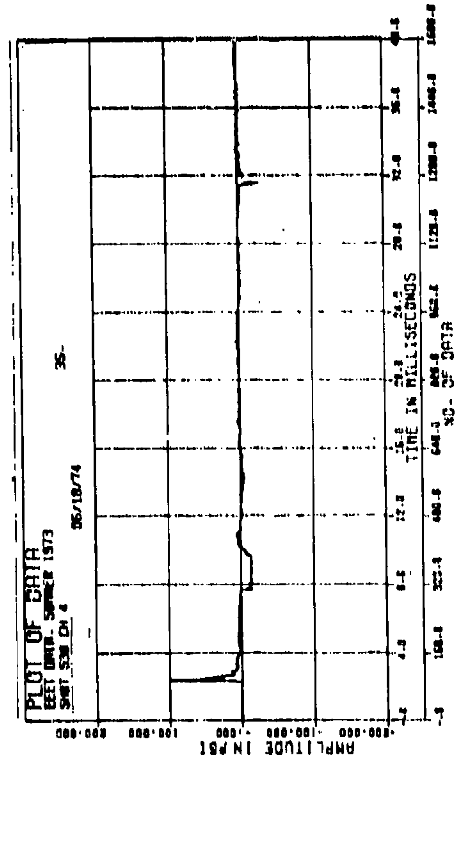
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05/18/74
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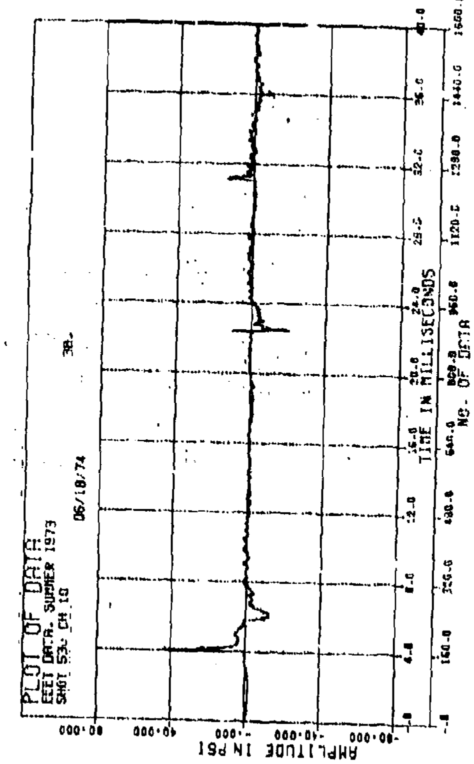
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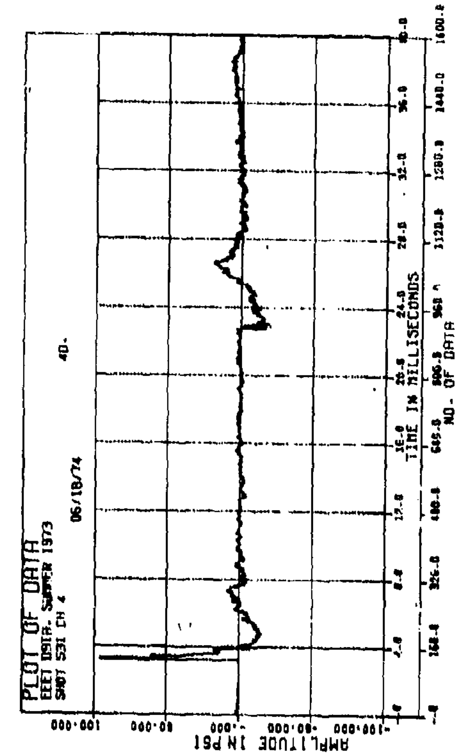
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SHOT 531 CH 4
06/18/74
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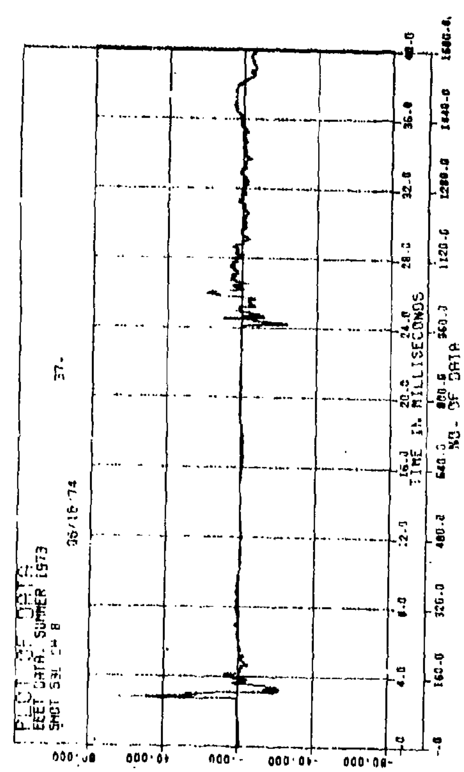
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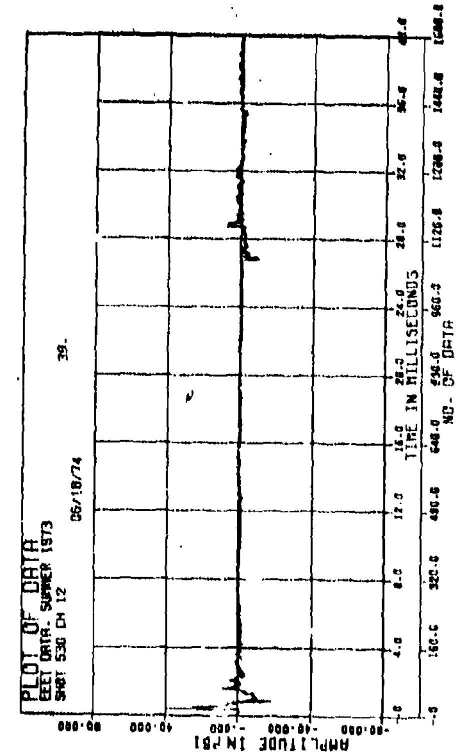
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06/18/74
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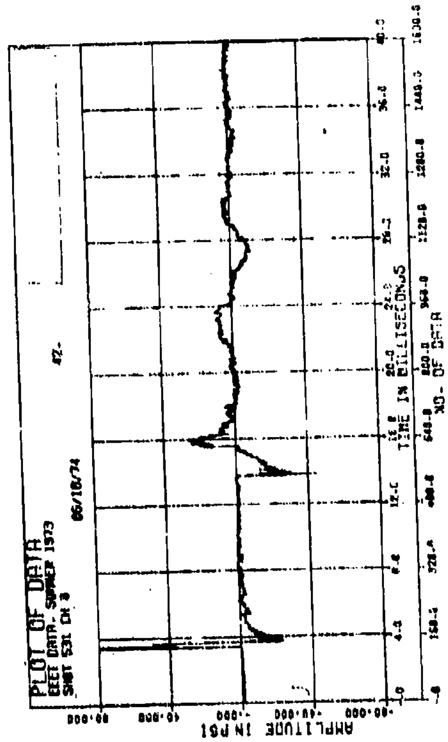
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05/18/74
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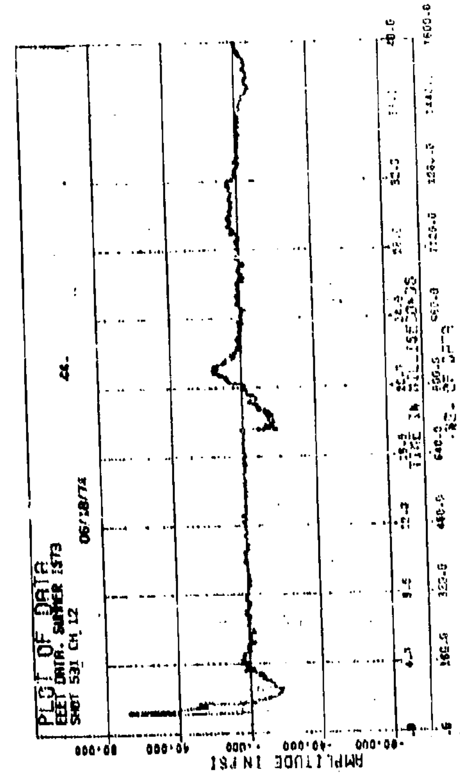
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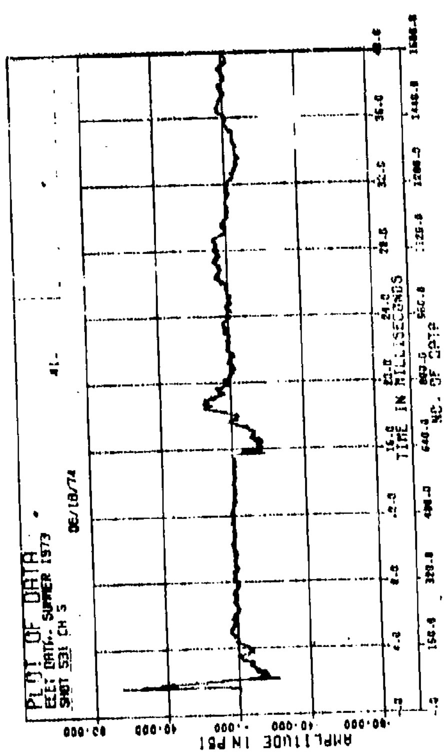
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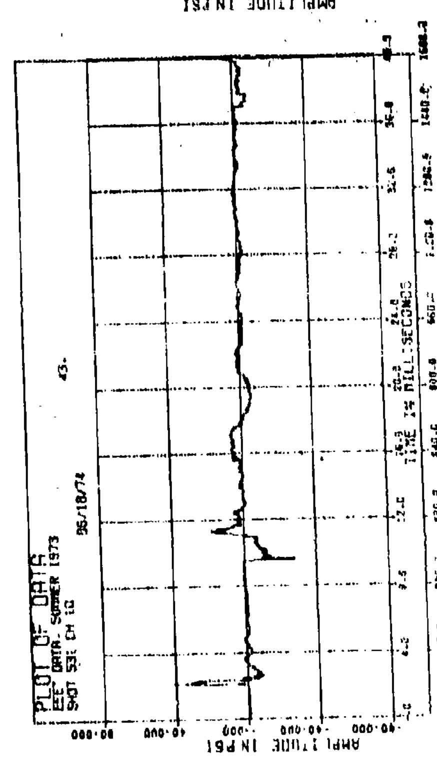
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EET DATA, SUMMER 1973
SHOT 531 CH 10
05/18/74
43.
TIME IN MILLISECONDS
NO. OF DATA
AMPLITUDE IN PSI

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